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POWER CALCULATIONS FOR ISENTROPIC COMPRESSIONS OF CRYOGENIC NITROGEN

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16. Abstract

A theoretical analysis has been made of the power required for isentropic compressions of cryogenic nitrogen in order to determine the extent to which the drive power for cryogenic tunnels might be affected by real-gas effects. The analysis covers temperatures from 80 to 310 K, pressures from 1.0 to 8.8 atm, and fan pressure ratios from 1.025 to 1.200. The power required to compress cryogenic nitrogen was found to be as much as 9.5 percent lower than that required to compress an ideal diatomic gas. Simple corrections to the ideal-gas values were found to give accurate estimates of the real-gas power values.

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SUMMARY

A theoretical analysis has been made of the power required for isentropic compressions of cryogenic nitrogen. This real-gas analysis was made from a cryogenic wind-tunnel perspective, and the purpose of the analysis was to determine the extent to which wind-tunnel drive power might be affected by the real-gas characteristics of nitrogen. The real-gas solutions covered stagnation temperatures from 80 to 310 K, stagnation pressures from 1.0 to 8.8 atm, and fan pressure ratios from 1.025 to 1.200. These solutions are compared to the ideal diatomic gas solutions. At cryogenic temperatures, the power required to compress nitrogen isentropically is as much as 9.5 percent lower than that required for the ideal gas. Simple corrections to the ideal values of mass flow, energy, and power were found to give accurate estimates of the real-gas values.

INTRODUCTION

The cryogenic wind-tunnel concept has been developed at the Langley Research Center in order to improve flight simulation in wind tunnels by increasing the test Reynolds number. The major advantages of increasing the Reynolds number by reducing the temperature of the test gas are given in references 1 to 4. For fan-driven tunnels, one of the prime advantages of reducing the temperature of the test gas is the accompanying reduction in the required drive power. The extent of this reduction is illustrated in figure 1 for three different wind-tunnel cases. In each case two of the three tunnel parameters (Reynolds number, stagnation pressure, and size) are held constant while the third varies with decreasing stagnation temperature. These calculations are based on the assumption of an ideal gas. However, for the cryogenic wind-tunnel concept as developed at Langley, cooling is accomplished with liquid nitrogen; the resulting test gas is cryogenic nitrogen. At these conditions, nitrogen has real-gas imperfections (ref. 5). Even though the analysis of reference 5 indicated that cryogenic nitrogen would be an acceptable test gas in terms of flow simulation, the real-gas characteristics could possibly become important in a wind-tunnel design consideration such as the drive power requirement.

This report presents the results of a study to determine the extent to which the wind-tunnel drive-power requirements might be affected by the real-gas characteristics of nitrogen. In this study, real-gas solutions for isentropic compressions of nitrogen were made for the range of operating temperatures (saturations to 310 K), pressures (1.0 to 8.8 atm), and tunnel pressure ratios (1.025 to 1.200) anticipated for fan-driven transonic cryogenic wind tunnels. The solutions were compared with those for an ideal diatomic gas, and the results are presented relative to the ideal-gas values. Real-gas calculations for tunnel throat conditions and for fan calculations are given in appendixes A and B. Program listing is given in appendix C.

SYMBOLS

a,b	constants
c	speed of sound, m/sec; W in computer program
c_p	specific heat at constant pressure, J/mole-K; CP in computer program
c_v	specific heat at constant volume, J/mole-K; CV in computer program
E	energy per unit mass, J/kgm
f	$= \frac{Z_{t,2}}{Z_{t,1}}$
h	specific enthalpy, J/mole-K; H in computer program
M	Mach number
$\dot{m}$	mass-flow rate per unit area, kgm/sec-m^2
P	power per unit area, J/sec-m^2
p	pressure, atm (1 atm = 1.013×10^5 Pa); P in computer program
R	gas constant for nitrogen, 296.791 J/kgm-K
r	pressure ratio, $p_{t,2}/p_{t,1}$
S	entropy, J/mole-K
T	temperature, K
V	velocity, m/sec; VEL in computer program
v	specific volume, liter/mole
Z	compressibility factor, pv/RT
γ	specific heat ratio, c_p/c_v
ρ	density, mole/liter; D in computer program

Superscript:

α isentropic expansion coefficient, $p = \rho^{\alpha}$ (Constant)

Subscripts:

1 upstream of fan

2 downstream of fan

amb ambient temperature, 310 K

i ideal-gas value

r real-gas or nitrogen value

S constant entropy

TH tunnel throat

TS test section

t stagnation condition

u increment

BASIC EQUATIONS

The test gas of a closed-circuit fan-driven wind tunnel is forced to flow around the circuit by the energy which is imparted to the gas by the fan. If the steady-flow compression that takes place at the fan is assumed to be a reversible adiabatic process (that is, isentropic), the energy per unit time, or power, which must be imparted to the gas is given by the equation

$$P = \dot{m}\left(h_{t,2} - h_{t,1}\right)_S \tag{1}$$

This equation holds for any gas and thus will be termed the real-gas power equation for isentropic compressions. This equation appears to be simple enough, but the two factors are not easily calculated. A later section will describe the method used in solving this real-gas equation.

The assumption of an ideal gas and the resulting expressions for isentropic flow allow this power equation to be expressed in an easily calculated form. An ideal gas as defined in this study is one that is both thermally and calorically perfect. The ideal-gas characteristics are:

$$\frac{pv}{RT} = 1$$

which is the equation of state,

$$\int dh = c_p \int dT$$

which gives the specific heats independent of T and p, and

$$c_p - c_v = R$$

In addition, the expressions that relate the static variables in an isentropic process are

$$p = \rho^{\gamma}(\text{Constant}) = T^{\frac{\gamma}{\gamma-1}}(\text{Constant})$$

By using these characteristics and expressions, equation (1) can be put into the following form:

$$P = \dot{m}\left[\frac{\gamma}{\gamma - 1} RT_{t,1}\left(r^{\frac{\gamma-1}{\gamma}} - 1\right)\right] \tag{2}$$

This ideal-gas power equation and the real-gas power equation (1) have been arranged to show two distinct factors. The first is the mass-flow rate, and the second represents the energy per unit mass for each case. This study analyzes the real-gas effects on the power required for isentropic compressions by examining the manner in which each of these factors is affected.

The mass-flow rate of any gas per unit area is given by

$$\dot{m} = \rho V$$

A subsequent section and appendix A describe the real-gas solutions for tunnel mass-flow rate. For isentropic flow of an ideal gas, this equation can be expressed as a function of the stagnation conditions and Mach number:

$$\dot{m}_i = \sqrt{\frac{\gamma}{R}} \frac{p_t}{\sqrt{T_t}} M\left(1 + \frac{\gamma - 1}{2} M^2\right)^{\frac{\gamma+1}{2(1-\gamma)}} \tag{3}$$

ANALYTICAL MODEL OF TUNNEL

The real-gas effects on the power required for isentropic compressions of nitrogen could be analyzed by assuming that the compressions take place in a constant-area duct where nitrogen is flowing at various temperatures, pressures, and velocities. However, since the impetus for this study evolved from the consideration of the power required for the operation of transonic cryogenic wind tunnels, the analysis will instead be made from this perspective.

A sketch of the analytical model of the tunnel is shown in figure 2. For this analysis the conditions upstream of the fan $p_{t,1}$ and $T_{t,1}$ and the pressure ratio r across the fan are the same for the real-gas and the ideal-gas cases. This assumption means that the outlet temperature $T_{t,2}$ is different for each case. With the assumption of no energy losses between the fan outlet and the tunnel throat (explained later), the stagnation conditions are the same at both of these locations. As a consequence, the test section or throat temperature $T_{t,2}$ is not the same for the real- and ideal-gas cases. It will be shown later that the difference between $\left(T_{t,2}\right)_r$ and $\left(T_{t,2}\right)_i$ is insignificant; therefore, for all practical purposes, the comparisons between the real and ideal gases are made at the same test-section conditions.

The tunnel mass flow will be calculated for the throat conditions (that is, $T_{t,2}$, $p_{t,2}$, and M_{TH}). For subsonic speeds, the throat and test-section Mach numbers are assumed to be identical. For supersonic speeds, the effective area of the test section has to be larger than that of the throat. In practice, this larger effective area is created either by diverging the walls of the test section or by allowing some of the mass of gas to flow through porous or slotted sections of the wall into the plenum chamber. In this latter case, the mass may be removed from the plenum by auxiliary suction, or it may reenter the test section at the diffuser entrance. For the analytical model used in this study, all the mass that passes through the tunnel throat is assumed to pass through the fan also.

For simplification, all the tunnel energy losses are assumed to occur between the throat of the tunnel and the fan. Data from existing transonic tunnels indicate that most of the losses do occur in this part of the tunnel because of the higher flow velocities. However, the results of this report could be used for other loss distributions if the fan energy and the throat mass flow were evaluated at the appropriate stagnation conditions.

For the cryogenic wind-tunnel concept, cooling is accomplished by evaporating liquid nitrogen in the tunnel flow, and as a result, mass is added to the stream at the cooler. It is anticipated that the cooling system would be placed upstream of the fan rather than downstream because the longer distance to the test section would permit more thorough mixing of the evaporating nitrogen with the main stream. This additional mass flow due to cooling is at most about 2 percent of the tunnel mass flow. A brief analysis which took this additional mass flow into consideration indicated that although the absolute level of power was up by 2 percent due to compression of this additional mass, the ratio of the real to the ideal power requirement was not significantly affected. Thus, for simplicity, cooling of this analytical model is assumed to occur without mass addition (mass-flow rate is identical at all tunnel locations).

Typical values of the fan pressure ratio which are necessary to achieve a given Mach number in the test section have been assumed for this analytical tunnel:

M_{TS}	r
0.2	1.025
.6	1.050
1.0	1.100
1.2	1.200

This Mach number pressure ratio correspondence is further assumed to be invariant with stagnation temperature and pressure.

This analytical model is assumed to have an operating stagnation pressure range of from 1.0 to 8.8 atm. The maximum pressure matches that of the proposed National Transonic Facility that is currently being designed (ref. 6). The stagnation temperatures cover the range from 310 K down to the saturated vapor temperature. Specifically, this lower limit of stagnation temperature at a given stagnation pressure is taken to be that temperature which causes the static temperature and pressure at the tunnel throat to be coincident with a point on the vapor pressure curve.

PROCEDURE FOR ANALYTICAL SOLUTIONS

Figure 3 shows a flow chart of a program that was written in order to calculate the power required for isentropic compressions of nitrogen and an ideal diatomic gas. This program uses a nitrogen properties program written at the National Bureau of Standards (ref. 7) that is based on Jacobsen's equation of state (ref. 8) It also makes use of some of the subprograms and procedures that were developed for the isentropic expansion study of reference 5. Appendix C gives a program listing and sample output.

As the flow chart shows, the program inputs are the test-section stagnation pressure $p_{t,2}$, Mach number M_{TS}, and the fan pressure ratio r. First, the program sets the test-section stagnation temperature for the real-gas or nitrogen case to a value of 310 K. Next, the program makes two sets of real-gas calculations. The first of these is the real-gas calculation of the tunnel throat conditions (block A). After the throat Mach number has been set, this routine determines the static flow properties which would result in the desired M_{TH}. When this procedure is completed, the real-gas mass-flow rate is determined. As these calculations are being made, a check is made to see whether the static flow properties have reached the saturated condition. If saturation occurs, the solutions are terminated. The details of the throat calculations of block A can be found in appendix A.

The other set of real-gas calculations is related to the fan as indicated by block B. Assuming isentropic compression, this routine takes the downstream stagnation conditions $p_{t,2}$ and $\left(T_{t,2}\right)_r$ and the fan pressure ratio and computes the upstream stagnation conditions $p_{t,1}$ and $T_{t,1}$. The real-gas energy per unit mass E_r is also determined and combined with the mass-flow rate from block A to give the real-gas power P_r for the compression. The details of these fan calculations are given in appendix B.

The next step in the program is to make the fan calculations for the ideal-gas case. The inlet stagnation conditions as determined from the real-gas calculations and the fan pressure ratio are used in these calculations. The outlet temperature is determined from the following isentropic relationship:

$$\left(T_{t,2}\right)_i = r^{\frac{\gamma-1}{\gamma}} T_{t,1}$$

The energy per unit mass is given by

$$E_i = \frac{\gamma}{\gamma - 1} RT_{t,1}\left(r^{\frac{\gamma-1}{\gamma}} - 1\right)$$

which is the second factor of basic equation (2).

After the ideal stagnation temperature $\left(T_{t,2}\right)_i$ has been determined, the ideal mass-flow rate at the throat is determined from basic equation (3). This mass-flow rate is combined with the energy per unit mass E_i to give the ideal power required for the compression.

At this point, the program prints out the real- and ideal-gas parameters associated with the compression and their relative values. With the completion of this solution, the real-gas temperature $T_{t,2}$ is decreased and the solution repeated. The temperature is incrementally decreased in this manner until the throat conditions for the real-gas case become saturated.

ANALYSIS OF SOLUTIONS

Isentropic power solutions of the type just described have been made for the analytical model of a cryogenic tunnel. The solutions cover a test-section Mach number range and a fan pressure ratio range from 0.2 to 1.2 and 1.025 to 1.200, respectively. Solutions covering these ranges were made at stagnation pressures from 1.0 to 8.8 atm and at stagnation temperatures from 310 K to saturation temperatures. This analysis examines the real-gas effects on the power for isentropic compressions by showing the effects on the two factors, mass-flow rate and energy per unit mass, that combine to give the power.

It should be remembered that the real- and ideal-gas solutions are for the same fan inlet conditions $p_{t,1}$ and $T_{t,1}$ and for a given pressure ratio r. The outlet pressure $p_{t,2}$ is the same, but the outlet temperatures are different. This difference is shown in figure 4 for the conditions which produce the maximum difference $r = 1.20$ and $p_{t,2} = 8.8$ atm. Even at the lowest inlet temperature, the real-gas value of downstream temperature differs from the ideal-gas value by less than 0.3 percent. Thus, for all practical purposes the following comparisons of real- and ideal-gas solutions are made at identical test-section stagnation conditions as well as for identical fan inlet conditions.

Energy for Isentropic Compressions

The real-gas effects of nitrogen on the energy per unit mass for isentropic compressions are shown in figure 5. The relative values (real to ideal) of energy are presented as a function of fan outlet temperature $T_{t,2}$ and for various values of outlet pressure $p_{t,2}$. Each curve is for a given fan pressure ratio. The fan outlet conditions $p_{t,2}$ and $T_{t,2}$ were chosen as the independent variables because these are the values for the tunnel throat and test section.

These figures show that the nitrogen values for energy per unit mass are always less than the ideal values. This difference increases as temperature is reduced. At the maximum pressure (fig. 5(d)), the real energy per unit mass is as much as 17 percent lower than the ideal diatomic gas value. These lower values of energy per unit mass for nitrogen could have been anticipated by comparing the curves for enthalpy against temperature at constant entropy (fig. 6). For the ideal gas, enthalpy is a function of temperature only. Along an isentrope, the enthalpy of nitrogen is a function of both temperature and pressure. Since the temperature dependence is dominant, however, the slope difference at a given temperature should be an indication of the energy ratio for the two cases. The slope for the nitrogen isentrope is less than that for the ideal gas.

Figure 5 also shows that the value of fan pressure ratio has an insignificant effect on the shape of the energy ratio-outlet temperature curve.

Figure 7 shows the effect of pressure on the energy ratio at constant temperatures. As can be seen, the energy ratio decreases nearly linearly with increasing pressure.

Real-Gas Effects on Tunnel Mass Flow

The relative values (real to ideal) of the tunnel mass flow are shown in figure 8 as a function of stagnation temperature for various values of stagnation pressure. As mentioned previously (fig. 4), the outlet stagnation temperatures were so near the same value for the real- and ideal-gas cases that these comparisons are at essentially the same throat conditions. Each curve is for a given throat Mach number.

As stagnation temperature is reduced, the mass-flow rates for nitrogen become increasingly greater than those for an ideal diatomic gas. At the maximum pressure (fig. 8(d)), the nitrogen mass-flow rate for $M_{TH} = 0.20$ and the minimum temperature is about 9.5 percent greater than the ideal-gas mass-flow rate. For $M_{TH} = 1.0$, the real mass flow is only about 7.0 percent greater due to the saturation temperature being higher than for the 0.2 case. The shape of the mass-flow—temperature curve is relatively insensitive to the throat Mach number.

Power for Isentropic Compressions

The real-gas effects on the power required for isentropic compressions are shown in figure 9. The relative power values are shown as a function of outlet or throat stagnation temperature for various values of stagnation pressure. These relative values are a combination of the relative energy ratios and the relative mass-flow ratios. The power values for the real gas are in general lower than those for the ideal gas. At the maximum pressure (fig. 9(d)) and minimum temperature, this reduction in the power required is about 9.5 percent for $M_{TS} = 0.2$ $(r = 1.025)$ and about 7.5 percent for $M_{TS} = 1.2$ $(r = 1.2)$. The shape of this power-ratio—temperature curve is essentially independent of the pressure ratio and/or Mach number. This independence is to be expected since the energy-ratio—temperature curve and the mass flow-temperature curve were essentially independent of the pressure ratio and Mach number, repectively. These power reductions due to real-gas effects are, of course, in addition to the large power reductions which result from operating at cryogenic temperature (fig. 1).

APPROXIMATE METHODS

For the engineering design of systems which utilize nitrogen, use of the complete calculation procedures of this report to include the real-gas effects on power calculations would be very cumbersome. Therefore, some approximate methods are now considered.

Energy Per Unit Mass

The following two equations are approximations for the energy required to compress a unit mass of real gas isentropically:

$$E_r = \frac{\gamma}{\gamma - 1} Z_{t,1} \frac{RT_{t,1}}{r - 1}\left\{\left(r^{\frac{\gamma-1}{\gamma}} - 1\right)(r - f) + \left[\frac{(\gamma - 1)(f - 1)}{2\gamma - 1}\right]\left(r^{\frac{2\gamma-1}{\gamma}} - 1\right)\right\} \tag{4}$$

$$E_r = Z_{t,2}E_i = Z_{t,2} \frac{\gamma}{\gamma - 1} RT_{t,1}\left(r^{\frac{\gamma-1}{\gamma}} - 1\right) \tag{5}$$

Equation (4) is the energy per unit mass portion of the power equation given in reference 9. It is a result of the energy equation

$$E_r = \int v\, dp$$

and the assumptions that the pressure-temperature relationship for the ideal gas remains valid

$$p = T^{\frac{\gamma}{\gamma-1}}(\text{Constant})$$

and that Z varies linearly with pressure along the isentrope

$$Z = (a + bp)_S$$

Equation (5) is derived with the same considerations, but Z is assumed to be constant along an isentrope. The data presented in figure 10 indicate that this is a reasonably good assumption.

Reference 9 indicates the actual values of specific heat ratio γ for the conditions prior to compression should be utilized in these equations. However, in reference 5, the isentropic expansion coefficients for nitrogen were found to remain near to the ideal diatomic gas value of 1.4. In addition, for this study, use of the ideal value of 1.4 gave more accurate results over the range of conditions considered herein than did use of the actual value of γ. For equation (5), the use of either $Z_{t,1}$ or $Z_{t,2}$ gives about the same degree of accuracy. For this report, $Z_{t,2}$ is used.

Figure 11 shows a comparison of these approximate equations with the exact real-gas solutions. Both of the approximate solutions are within 0.5 percent of the exact values. Although equation (4) gives excellent values for the energy per unit mass, it is unnecessarily complex for the range of conditions considered herein. Simply multiplying the ideal values by the compressibility factor $Z_{t,2}$ gives results which are equally accurate.

Mass Flow

The mass flow per unit area is $\dot{m} = \rho V$. This equation may be rewritten in the following form:

$$\dot{m} = \frac{\rho}{\rho_t} \rho_t M c$$

The ratio of the real-gas mass flow $\dot{m}_r$ to the ideal-gas mass flow $\dot{m}_i$ at a given Mach number would be

$$\frac{\dot{m}_r}{\dot{m}_i} = \frac{(\rho/\rho_t)_r}{(\rho/\rho_t)_i} \frac{1}{Z_t} \frac{c_r}{c_i}$$

If $p = \rho^{\alpha}(\text{Constant})$ is approximately valid for the real gas, and α remains near 1.4 (ref. 5), then

$$\frac{c_r}{c_i} \approx \sqrt{Z} \approx \sqrt{Z_t}$$

Also $\dfrac{(\rho/\rho_t)_r}{(\rho/\rho_t)_i} \approx 1.0$ (from ref. 5). With these considerations,

$$\frac{\dot{m}_r}{\dot{m}_i} \approx \sqrt{\frac{1}{Z_t}}$$

The accuracy of this simple approximation is illustrated in figure 12. For the range of conditions considered in this report, this approximation is accurate to about 0.5 percent.

Power

If $\dfrac{E_r}{E_i} \approx Z_{t,2}$ and $\dfrac{\dot{m}_r}{\dot{m}_i} \approx \sqrt{\dfrac{1}{Z_{t,2}}}$, then $\dfrac{P_r}{P_i} \approx \sqrt{Z_{t,2}}$. Figure 13 illustrates the accuracy of this simple approximation. For the range of conditions considered herein, the accuracy is within about 0.5 percent.

The results just presented indicate that simple corrections to the ideal-gas values of mass flow, compression energy, and compression power give accurate values for the real-gas case.

CONCLUSIONS

In this report, an analysis has been made of the real-gas effects of nitrogen on the power required for steady-flow isentropic compressions. The compressions are assumed to occur at the fan of a transonic cryogenic wind tunnel. The analytic model tunnel was assumed to operate at stagnation temperatures from 310 K to saturation and at stagnation pressures from 1.0 to 8.8 atm. The results of this anlysis led to the following conclusions:

1. The energy to compress a unit mass of nitrogen at cryogenic temperatures is less than that required for the ideal gas. For the maximum pressure-minimum temperature conditions, this reduction in energy is on the order of 14 to 17 percent.

2. Tunnel mass flow at a given Mach number is higher for cryogenic nitrogen than for the ideal gas.

3. The power for isentropic compressions of cryogenic nitrogen is also less than that required for the ideal gas. At the maximum-pressure—minimum-temperature conditons, this reduction in power is on the order of 7.5 to 9.5 percent. The power decrease is less than the energy decrease because of the increase in mass flow.

4. Simple compressibility factor corrections to the ideal values of mass flow, energy, and power give very accurate estimates of the real-gas values.

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APPENDIX A

TUNNEL THROAT CONDITIONS - REAL-GAS CALCULATIONS

Figure 14 contains a flow chart of the part of the program that makes the real-gas calculations of the throat conditions. The variables required for this part of the program are shown at the top of the chart. A step-by-step description of the calculations that occur at each block of the flow chart follows. All variables should be assumed to be real-gas variables except those specifically identified as ideal (subscript i).

Step 1 Subroutine PROP from the National Bureau of Standards (NBS) program is used to calculate the stagnation enthalpy $h_{t,2}$ and entropy $S_{t,2}$.

Step 2 An initial guess for the static conditions $\left(p_i,\ \rho_i,\text{ and } T_i\right)$ is made by using the appropriate ideal-gas equations.

Step 3 The real-gas value of static temperature T is initialized to the ideal value T_i and T is established as the iterative variable in order to force the solutions to converge on the desired M_{TH}.

Step 4 Function DSFND iteratively solves for ρ from the entropy equation $S_{t,2} = S(\rho,T)$.

Step 5 Subroutine PROP gives values for static pressure p and static enthalpy h by using T and ρ from steps 3 and 4, respectively.

Step 6 If the static temperature T and static pressure p are coincident with a point on the vapor pressure curve or if they lie in the liquid region, the solution is terminated.

Step 7 Subroutine VSND (NBS program) calculates the velocity of sound c with T and ρ as inputs.

Step 8 Subroutine MVCAL calculates the velocity and Mach number from these equations:

$$V = \sqrt{2\left(h_{t,2} - h\right)}$$

$$M = \frac{V}{c}$$

Step 9 The mass-flow rate per unit area is now calculated

$$\dot{m} = \rho V$$

Step 10 The calculated Mach number M is checked to see whether it is within 0.00001 of the desired M_{TH}. If it is, the solution for the throat conditions is complete and the mass-flow rate is printed out.

Step 11 If the Mach convergence is not satisfactory, subroutine TCHANG finds the slope of the temperature Mach number curve $\Delta T/\Delta M$ for a constant entropy $S_{t,2}$. A linear adjustment is made to the static temperature T as required for Mach convergence.

Step 12 This adjusted T is returned to step 3 for the next iteration, and steps 3 to 12 are repeated until the Mach convergence criterion is met at step 10.

APPENDIX B

FAN CALCULATIONS - REAL GAS

Presented in figure 15 is a flow chart of the part of the program that calculates the fan conditions for the real-gas (nitrogen) case. The objectives of this part of the program are to obtain an isentropic solution for the upstream stagnation quantities $p_{t,1}$ and $T_{t,1}$ and then to calculate the energy per unit mass E and the power P required for the compression. The downstream conditions $p_{t,2}$, $T_{t,2}$, $S_{t,2}$, and $h_{t,2}$, the fan pressure ratio r, and the tunnel mass-flow rate $\dot{m}$ are required as inputs to this part of the program. The following is a step-by-step description of the calculations that occur at each block of the flow chart. Again, all variables should be assumed to be real-gas variables except those specifically identified as ideal (subscript i).

Step 1 The fan inlet pressure is calculated directly as shown. Note that $p_{t,1}$ and $p_{t,2}$ have the same values for both the real- and ideal-gas cases.

Step 2 An initial guess for the fan inlet temperature $\left(T_{t,1}\right)_i$ is made using the ideal-gas equation.

Step 3 $T_{t,1}$ is set up for iteration in order to force the upstream entropy $S_{t,1}$ to be the same as the downstream entropy $S_{t,2}$ (see step 6).

Step 4 Subroutine PROP is called with $p_{t,1}$ and $T_{t,1}$ to give values for the upstream enthalpy $h_{t,1}$ and entropy $S_{t,1}$.

Step 5 The upstream temperature is increased by a factor of 1.001 and is used in subroutine PROP with $p_{t,1}$ to give another point of the entropy-temperature curve $\left(S_{t,1}\right)_u$.

Step 6 A comparison of $S_{t,1}$ and $S_{t,2}$ is made to see whether these two entropies agree to within 1×10^{-8}.

Step 7 If the two entropies have not converged sufficiently, a temperature-entropy slope is calculated from the information of steps 4 and 5.

Step 8 This temperature-entropy slope is used to adjust $T_{t,1}$ to account for the difference in the inlet and outlet entropies $S_{t,2} - S_{t,1}$, and the adjusted $T_{t,1}$ is returned to step 3 for the next iteration.

Step 9 When the convergence criteria of step 6 are finally satisfied, the energy and power are calculated.

Step 10 The solution is complete, and the fan inlet conditions and power values are stored for utilization in other parts of the program.

APPENDIX C

PROGRAM LISTING AND SAMPLE OUTPUT

Presented here is a listing of the program that was developed in order to calculate the power and energy required to compress nitrogen and the ideal diatomic gas isentropically. This program is a modification of those of references 5 and 7. In addition, a sample output is presented.

Program Listing

```
      PROGRAM N2POWER(INPUT,OUTPUT,TAPE5=INPUT,TAPE3=OUTPUT)
      CALL DATA N2
C
C THIS PROGRAM CALCULATES THE POWER REQUIREMENTS FOR ISENTROPIC
C COMPRESSIONS OF BOTH NITROGEN AND AN IDEAL DIATOMIC GAS
C
      READ 100, NC
  100 FORMAT (I5)
C
C THESE POWER REQUIREMENTS ARE CALCULATED FOR A SPECIFIED NUMBER OF
C CASES (NC), EACH OF WHICH INVOLVES KNOWN VALUES FOR THE TEST-SECTION
C MACH NUMBER (BM2), FAN OUTLET PRESSURE (POT), AND THE RATIO OF FAN
C OUTLET TO INLET PRESSURE (PR4)
C
C THE POWER AND MASS-FLOW RATE CALCULATIONS INVOLVE CROSS-SECTIONAL
C AREAS WHICH CORRESPOND TO THE THROAT AREA OF THE TEST SECTION
C
      DO 500 L = 1,NC
      READ 200, POT, PR4, BM2
  200 FORMAT (3F10.0)
      PRINT 210, BM2, PR4, POT, (POT/PR4)
  210 FORMAT (1H1,32X,*ENEPGY AND POWER REQUIREMENTS FOR FAN-DRIVEN CRYO
     1GENIC WIND TUNNEL*/49X,*ISENTROPIC COMPRESSION IN NITROGEN*///2X,*
     2TEST-SECTION MACH NUMBER =*,F5.2/2X,*FAN PRESSURE RATIO*,7X,*=*,F7
     3.4,*     */2X,*FAN PRESSURE, OUTLET*,5X,*=*,F7.4,* ATM*/2X,*FAN PRE
     4SSURE, INLET*,6X,*=*,F7.4,* ATM*///2X,*E = FAN ENERGY*/2X,*P = FAN
     5 POWER*///11X,17(*-*),*REAL GAS*,17(*-*),4X,17(*-*),*IDEAL GAS*,16
     6(*-*),4X,5(*-*),*REAL/IDEAL VALUES*,4(*-*)/2X,*TT,IN*,4X,2(*TT,OUT
     7*,6X,*MDOT*,7X,*E/MASS*,6X,*P/AREA*,5X),1X,*MDOT*,5X,*E/MASS*,4X,*
     8P/AREA*/4X,*K*,8X,2(*K*,7X,*KGM/S-M2*,5X,*J/KGM*,7X,*J/S-M2*,7X)/)
C
C FOR EACH CASE, THE CALCULATIONS ARE PERFORMED FOR EACH OF
C INCREMENTALLY DECREASING VALUES OF FAN OUTLET TEMPERATURE (TOT) UNTIL
C SATURATION CONDITIONS ARE REACHED
C
      DO 280 I=1,50
      IF ( I .GT. 20) GO TO 205
      TOT= 320. - I * 10
      GO TO 206
  205 TOT = 120. - (I-20) * 5
```

APPENDIX C

```
C
C THE LIQUID REGION CONDITION IS REACHED WHEN THE TEMPERATURE FALLS
C BELOW THAT OF THE CRITICAL POINT, AND THE PRESSURE RISES ABOVE THE
C CORRESPONDING SATURATION PRESSURE (PSAT)
C
C THE CRITICAL POINT FOR NITROGEN IS AT PRESSURE = 33.5 ATM AND AT
C TEMPERATURE = 126 DEGREES KELVIN
C
C WHEN THIS SITUATION OCCURS, THEN THE NEXT CASE MUST BE CONSIDERED
C
  206 PSAT =33.5
      IF (TOT .LT. 126) PSAT = VPN(TOT)
      IF (POT .GT. PSAT) GO TO 385
C
C USING THE KNOWN PROPERTIES OF NITROGEN, THE DENSITY (DOT), ENTHALPY
C (HOT), AND ENTROPY (SOT), AT THE OUTLET OF THE FAN, CAN BE CALCULATED
C
      CALL PROP(TOT,POT,DOT,1,HOT,SOT,U)
C
C STATIC CONDITIONS AT THE TUNNEL THROAT WHICH CORRESPOND TO THE DESIRED
C THROAT MACH NUMBER ARE ESTIMATED BY ASSUMING ISENTROPIC FLOW OF IDEAL
C GAS FROM FAN OUTLET TO THROAT
C
C T IS THE TEMPERATURE
C D IS THE DENSITY
C P IS THE PRESSURE
C
      BM3=BM2
      IF (BM3.GT.1.0) BM2=1.0
      T = 1./(1.+BM2**2./5.)*TOT
      D = DOT*(T/TOT)**2.5
      P = POT*(T/TOT)**3.5
C
C ANOTHER TEST FOR SATURATION CONDITIONS
C
      PSAT = 33.5
      IF(T.LT.126.) PSAT = VPN(T)
      IF (P   .GT. PSAT) GO TO 385
C
C THE THROAT TEMPERATURE IS VARIED UNTIL THE REAL-GAS ISENTROPIC
C SOLUTION CONVERGES ON THE DESIRED THROAT MACH NUMBER
C
C H IS THE ENTHALPY
C S IS THE ENTROPY
C
C BMACH IS THE TRIAL MACH NUMBER
C VEL   IS THE FLOW VELOCITY
C QN2   IS THE MASS-FLOW RATE FOR THE REAL-GAS CASE
C
      DO 217 K= 1,100
      D = DSFND(SOT,T,D)
      CALL PROP(T,P,D,2,H,S,U)
```

```
C
C ANOTHER TEST FOR SATURATION CONDITIONS
C
      PSAT = 33.5
      IF(T.LT.126.) PSAT = VPN(T)
      IF (P   .GT. PSAT) GO TO 385
      CALL VSND(T,P,D,2,W)
      CALL MQRCAL(HOT,H,D,T,W,BMACH,QN2,REY)
      CALL MVCAL(HOT,H,W,BMACH,VEL)
      QN2= 28.0134 *D*VEL
      IF (ABS(BMACH-BM2)-.00001) 218, 218, 216
  216 IF (K.EQ.100) GO TO 330
      CALL TCHANG(BMACH,BM2,T,D,SOT,HOT)
  217 CONTINUE
C
C THESE ARE THE FAN INLET PRESSURE (P) AND AN ESTIMATE OF THE FAN
C INLET TEMPERATURE (T)
C
  218 P = POT/PR4
      T = TOT/PR4**.2857
C
C NOW THE PROGRAM VARIES FAN INLET TEMPERATURE SO THAT THE INLET
C ENTROPY CONVERGES TO THE OUTLET AND/OR TEST-SECTION VALUE (ISENTROPIC
C COMPRESSION)
C
C TU IS THE INCREMENTED TEMPERATURE
C SU IS THE CORRESPONDINGLY INCREMENTED ENTROPY
C
      DO 260 J=1,100
      TU = 1.001 * T
      CALL PROP(T,P,D,1,H,S,U)
      CALL PROP(TU,P,DU,1,HU,SU,U)
      IF (ABS(S-SOT) -1.E-08 * SOT) 265,265,256
  256 T= T + (TU-T)/(SU-S) * (SOT-S) * .6
      IF ( J .EQ. 100) GO TO 406
  260 CONTINUE
C
C NOW THAT ALL OF THE NECESSARY CONDITIONS FOR THE TUNNEL HAVE BEEN
C DETERMINED, THE POWER REQUIREMENTS CAN BE CALCULATED AND PRINTED OUT
C
C EN1  IS THE ENERGY REQUIREMENT PER UNIT MASS FOR THE REAL-GAS CASE
  265 EN1 = 35.697*(HOT-H)
C R IS THE NITROGEN GAS CONSTANT, IN J/KGM-K
      R = 296.791
C TOI  IS THE OUTLET TEMPERATURE FOR THE IDEAL-GAS CASE
      TOI = PR4**.2857*T
C EN2  IS THE ENERGY REQUIREMENT PER UNIT MASS FOR THE IDEAL-GAS CASE
      EN2 = 3.5*R*T*(PR4**.2857-1.0)
C EN3  IS THE RATIO OF REAL TO IDEAL ENERGY PER UNIT MASS REQUIREMENT
      EN3 = EN1/EN2
```

APPENDIX C

```
C HP1  IS THE FAN POWER REQUIRED PER UNIT CROSS-SECTIONAL AREA FOR THE
C       REAL-GAS CASE
      HP1 = EN1*QN2
C QN2I IS THE MASS-FLOW RATE FOR THE IDEAL CASE
      QN2I = SQRT(1.4/(9.74015E-11*R*TOI))*POT*BM2/(1.+BM2**2./5.0)**3.0
      BM2=BM3
C QN3  IS THE RATIO OF REAL TO IDEAL MASS-FLOW RATE
      QN3 = QN2/QN2I
C HP2  IS THE FAN POWER REQUIRED PER UNIT CROSS-SECTIONAL AREA FOR THE
C       IDEAL-GAS CASE
      HP2 = EN2*QN2I
C HP3  IS THE RATIO OF REAL TO IDEAL POWER REQUIRED PER UNIT CROSS-
C       SECTIONAL AREA
      HP3 = HP1/HP2
C
       PRINT 270,T,TOT,QN2,EN1,HP1,TOI,QN2I,EN2,HP2,QN3,EN3,HP3
  270 FORMAT(F7.1,2(F9.1,2F12.1,E13.4),3F10.4)
  280 CONTINUE
       GO TO 500
  330 PRINT 340
  340 FORMAT(*  TEMP-MACH DID NOT CONVERGE IN LOOP 217*)
       GO TO 500
  385 PRINT 390
  390 FORMAT(*  SATURATION CONDITIONS REACHED AT THROAT MACH NUMBER*)
       GO TO 500
  406 PRINT 407
  407 FORMAT(*  TEMP-ENTROPY DID NOT CONVERGE IN LOOP 260*)
  500 CONTINUE
      STOP
      END


      SUBROUTINE CPVTD(T,D,CP,CV)
      COMMON /CRPR/ CR(3) /METH/ M
      COMMON /RFPR/ RF(10)
C
C.... ROUTINE TO CALCULATE CV AND CP FROM THE EQUATION OF STATE
C.... WRITTEN 7/21/71 A MYERS
C.... REVISED 12/5/71 A MYERS
C
      DC=CR(2)
      TC=CR(3)
      R =RF(5)
      AK=RF(6)
      CALL PFND(T,D,P)
      IF(M.EQ.1)GO TO 1
      IF(T.GT.TC)GO TO 1
      IF(D.GT.DC)GO TO 2
    1 CVO=CPIG(T)-(R*AK)
      CV=CVO-(FING3(T,D)-FING3(T,0.00))*AK
    3 F1=T/D**2
      F2=DPDT(T,D)
      F3=DPDD(T,D)
      CP=CV+(F1*F2**2/F3)*AK
      RETURN
```

```
    2 DT=0.1
      T1=T+DT
      T2=T-DT
      CALL LPROP(T1,P1,D,1,H,S,U1)
      CALL LPROP(T2,P2,D,1,H,S,U2)
      CV=(U1-U2)/(2.00*DT)
      GO TO 3
      END


      SUBROUTINE DATAN2
      COMMON /CEOS/G(41) /CVPN/GV(11) /CIGCP/GI(9) /CSL/CL(7) /CSV/CV(7)
     .        /CRPR/CR(3) /CTEVP/CT(8) /RFPR/RF(10) /METH/ M
C
C.... IF THE PROPERTIES OF NITROGEN ARE TO BE CALCULATED, A CALL TO THIS
C.... SUBROUTINE MUST BE THE FIRST CALL STATEMENT IN THE MAIN PROGRAM
C
C.... THE COMMON BLOCKS INITIALIZED IN THIS ROUTINE HOLD THE FOLLOWING
C.... INFORMATION -
C
C         /CEOS/ G(41)    COEFFICIENTS OF THE EQUATION OF STATE
C
C         /CIGCP/ CIG(9)  COEFFICIENTS OF THE IDEAL-GAS HEAT CAPACITY EQUATION
C
C         /CVPN/ GG(11)   COEFFICIENTS OF THE VAPOR PRESSURE EQUATION
C
C         /CRPR/ CR(3)    THE CRITICAL PROPERTIES IN THE SAME UNITS AS THE
C                         EQUATION OF STATE
C                         CR(1)=CRITICAL PRESSURE
C                         CR(2)=CRITICAL DENSITY
C                         CR(3)=CRITICAL TEMPERATURE
C
C         /CSL/ SL(7)     COEFFICIENTS OF EQUATION USED TO APPROXIMATE
C                         THE SATURATED LIQUID DENSITY AS A FUNCTION OF
C                         TEMPERATURE
C
C
C         /RFPR/ RF(10)   REFERENCE PROPERTIES
C                         RF(1)=REFERENCE ENTHALPY AT TEMPERATURE TOH
C                         RF(2)=REFERENCE ENTROPY AT TEMPERATURE TOS
C                         RF(3)=TEMPERATURE TOH
C                         RF(4)=TEMPERATURE TOS
C                         RF(5)=GAS CONSTANT IN UNITS OF EQUATION OF STATE - R
C                         RF(6)=CONVERSION FACTOR TO CHANGE UNITS OF
C                               THE EQUATION OF STATE TO DESIRED ENERGY UNITS
C                         RF(7)=MOLECULAR WEIGHT
C                         RF(8)=TRIPLE POINT TEMPERATURE
C                         RF(9)   - NOT USED
C                         RF(10)  - NOT USED
C
C         /METH/ M        INDICATES METHOD TO BE USED IN THE CALCULATION
C                         OF LIQUID PROPERTIES
C                         M=1  INDICATES ISOTHERM INTEGRATION THROUGH THE DOME
C                         M=2  INDICATES THE USE OF THE CLAPEYRON EQUATION
C                              THROUGH THE DOME
```

APPENDIX C

```
M=1
G( 1)=     0.136224769272827D-02
G( 2)=     0.107032469908591D 00
G( 3)=    -0.243900721871413D 01
G( 4)=     0.341007449376470D 02
G( 5)=    -0.422374309466167D 04
G( 6)=     0.105098600246494D-03
G( 7)=    -0.112594826522081D-01
G( 8)=     0.142600789270907D-03
G( 9)=     0.184698501609007D 05
G(10)=     0.811140082588776D-07
G(11)=     0.233011645038006D-02
G(12)=    -0.507752586350986D 00
G(13)=     0.485027881931214D-04
G(14)=    -0.113656764115364D-02
G(15)=    -0.707430273540575D 00
G(16)=     0.751706648852680D-04
G(17)=    -0.111614119537424D-05
G(18)=     0.368796562233495D-03
G(19)=    -0.201317691347729D-05
G(20)=    -0.169717444755949D 05
G(21)=    -0.119719240044192D 06
G(22)=    -0.975218272038281D 02
G(23)=     0.554639713151823D 05
G(24)=    -0.179920450443470D 00
G(25)=    -0.256582926077184D 01
G(26)=    -0.413707715090789D-03
G(27)=    -0.256245415300293D 00
G(28)=    -0.124222373740063D-06
G(29)=     0.103556535840165D-04
G(30)=    -0.538699166558303D-09
G(31)=    -0.757415412839596D-08
G(32)=     0.585367172069521D-07
G(41)=    -0.560000000000000D-02
GV(1)= 0.8394409444D 04
GV(2)=-0.1890045259D 04
GV(3)=-0.7282229165D 01
GV(4)=0.0D0
GV(5)= 0.5556063825D-03
GV(6)=-0.5944544662D-05
GV(7)= 0.2715433932D-07
GV(8)=-0.4879535904D-10
GV(9)= 0.5095360824D 03
GV(10)= 0.1022850966D-01
GV(11)=     0.195000000000000D 01
GI(1)=    -0.735210401157252D 03
GI(2)=     0.342239980411978D 02
GI(3)=    -0.557648284567620D 00
GI(4)=     0.350404228308756D 01
GI(5)=    -0.173390185081005D-04
GI(6)=     0.174650849766463D-07
GI(7)=    -0.356892033544348D-11
GI(8)=     0.100538722808834D 01
GI(9)=     0.335340610000000D 04
CL(1)=     0.194244031922000D 02
CL(2)=     0.570837481942000D 02
CL(3)=    -0.243269850463000D 03
```

```
      CL(4)=     0.885168381502000D 03
      CL(5)=    -0.163936797734000D 04
      CL(6)=     0.115743200533000D 04
      CL(7)=     0.101822098327000D 01
      CV(1)=     0.163333455388000D 01
      CV(2)=    -0.940437709170000D 01
      CV(3)=     0.218527460266000D 02
      CV(4)=    -0.102687437637000D 03
      CV(5)=     0.187949744862000D 03
      CV(6)=    -0.164024367971000D 03
      CV(7)=    -0.957316390316000D-01
      CR(1)=33.555D0
      CR(2)=11.21D0
      CR(3)=126.2D0
      CT(1)=    -0.142064786200000D-02
      CT(2)=     0.129088086900000D-01
      CT(3)=     0.0
      CT(4)=     0.0
      CT(5)=     0.0
      CT(6)=     0.0
      CT(7)=     0.0
      CT(8)=     0.0
      RF(1)=8.669D03
      RF(2)=191.502D00
      RF(3)=298.15D00
      RF(4)=298.15D00
      RF(5)=     0.820539000000000D-01
      RF(6)=     0.101327800000000D 03
      RF(7)=28.0134D0
      RF(8)=63.148D0
      RETURN
      END


      SUBROUTINE DCALC(D,T,P,DL,DH)
      DATA(MAX=30)
      DATA(EPS=1.E-5)
C
C.... ROUTINE TO PERFORM ITERATIVE SOLUTION OF THE EQUATION OF STATE
C
C.... DL IS LOWER BOUND ON DENSITY
C.... DH IS UPPER BOUND ON DENSITY
C
C.... THE DESIRED DENSITY MUST LIE BETWEEN DL AND DH
C
C.... ALGORITHM IS MODIFIED VERSION OF
C
C.... *A QUADRATIC FORMULA FOR FINDING THE ROOT OF AN EQUATION*  BY
C.... LI. G. CHAMBERS MATHEMATICS OF COMPUTATION VOL 25 NO 114 APRIL (1971)
C
C.... WRITTEN 2/7/72  A MYERS
```

APPENDIX C

```
C
      IDS=0
      IC=0
    2 CONTINUE
      D1=DL
      D2=DH
      CALL PFND(T,D1,P1)
      CALL PFND(T,D2,P2)
      Y1=P1-P
      Y2=P2-P
    1 IC=IC+1
      IF(IC.GT.MAX)GO TO 5
      IF(IDS.EQ.1)GO TO 7
      IF(IC.GT.20)GO TO 6
      DS=(D1*Y2-D2*Y1)/(Y2-Y1)
      GO TO 8
    7 DS=(D1+D2)/2.00
    8 CONTINUE
      CALL PFND(T,DS,PS)
      YS=PS-P
      D3=DS*Y1*Y2/((YS-Y2)*(YS-Y1)) +
     .   D1*YS*Y2/((Y1-Y2)*(Y1-YS)) +
     .   D2*YS*Y1/((Y2-Y1)*(Y2-YS))
      CALL PFND(T,D3,P3)
      Y3=P3-P
      IF( ABS(Y3).LE.EPS)GO TO 3
      IF(Y3.GT.0.00)GO TO 12
      IF(Y3.LT.Y1)GO TO 12
      Y1=Y3
      D1=D3
   12 IF(YS.GT.0.00)GO TO 13
      IF(YS.LT.Y1)GO TO 13
      Y1=YS
      D1=DS
   13 IF(Y3.LT.0.00)GO TO 14
      IF(Y3.GT.Y2)GO TO 14
      Y2=Y3
      D2=D3
   14 IF(YS.LT.0.00)GO TO 1
      IF(YS.GT.Y2)GO TO 1
      Y2=YS
      D2=DS
      GO TO 1
    3 CONTINUE
      D=D3
      RETURN
    5 WRITE(3,300)T,P,DL,DH,D1,Y1,D2,Y2,DS,YS,D3,Y3
```

```
  300 FORMAT(*---DCALC FAILED TO CONVERGE---*/
     .        *      T  = *,F15.7,/,
     .        *      P  = *,F15.7,/,
     .        *      DL = *,F15.7,/,
     .        *      DH = *,F15.7,/,
     .        *      D1 = *,F15.7,/,
     .        *      Y1 = *,F15.7,/,
     .        *      D2 = *,F15.7,/,
     .        *      Y2 = *,F15.7,/,
     .        *      DS = *,F15.7,/,
     .        *      YS = *,F15.7,/,
     .        *      D3 = *,F15.7,/,
     .        *      Y3 = *,F15.7)
      D=DS
      RETURN
    6 CONTINUE
      IDS=1
      IC=0
      GO TO 2
      END
```

```
      SUBROUTINE DFND(T,P,D,K)
      COMMON /RFPR/ RF(10)
      COMMON /CRPR/CR(3)
C
C.... ROUTINE TO GENERATE TRIAL DENSITIES FOR ITERATIVE SOLUTION OF
C.... THE EQUATION OF STATE FOR DENSITY GIVEN TEMPERATURE AND PRESSURE
C
C     K =0  INDICATES SINGLE PHASE POINT
C     K =1  INDICATES T + P ARE FOR THE SATURATED LIQUID
C     K =2  INDICATES T + P ARE FOR THE SATURATED VAPOR
C
C.... WRITTEN 2/10/72  A MYERS
C
      IF((K.LE.2).AND.(K.GE.0))GO TO 1
      WRITE(3,300)K
  300 FORMAT(27H *** ERROR IN CALL DFND ***,/,
     .        *      K MUST EQUAL 0, 1, OR 2*,/,
     .        *      K = *,I10)
      RETURN
    1 PC=CR(1)
      DC=CR(2)
      TC=CR(3)
      IF(K.GT.0)GO TO 5
      IF(T.GE.TC)GO TO 2
      VP=VPN(T)
      IF(P.LE.VP)GO TO 3
    4 DH=3.100*DC
      DL=DSATL(T)
      CALL DCALC(D,T,P,DL,DH)
      RETURN
    3 DL=0
      DH=DSATV(T)
      CALL DCALC(D,T,P,DL,DH)
      RETURN
```

```
    2 DL=0
      DH=3.100*DC
      IF((T.GT.1000.00).AND.(P.LT.300.00))DH=DC
      CALL DCALC(D,T,P,DL,DH)
      RETURN
    5 IF(K.EQ.1)GO TO 4
      GO TO 3
      END


      SUBROUTINE DPDTVP(T,P,DPDT)
      COMMON/CVPN/G(11) /CRPR/CR(3)
      COMMON /SCRH/ X(40)
C
C.... CALCULATE DP/DT FOR THE VAPOR PRESSURE EQUATION
C
C.... WRITTEN 7/22/71 A MYERS
C
      TC=CR(3)
      A=G(11)
      T2=T*T
      T3=T*T2
      T4=T*T3
      T5=T*T4
      X(1)=-1.00/T2
      X(2)=0
      X(3)=1.00
      X(4)=2.00*T
      X(5)=3.00*T2
      X(6)=4.00*T3
      X(7)=5.00*T4
      X(8)=6.00*T5
      X(9)=1.00/T
      X(10)=(TC-T)**(A-1.00)*(-A)
      DPDT=0
      DO 1 I=1,10
    1 DPDT=DPDT+X(I)*G(I)
      DPDT=DPDT*P
      RETURN
      END


      SUBROUTINE LPROP(T,P,D,K,H,S,U)
      COMMON /RFPR/ RF(10)
      COMMON /METH/ M
C
C.... ROUTINE TO CALCULATE THE PROPERTIES OF THE LIQUID
C.... WRITTEN 7/20/71 A MYERS
C.... REVISED 12/8/71 A MYERS
C
C     K =1    INPUT IS T + D
C     K =2    INPUT IS T + P
C     K =3    INPUT IS T, P, + D
C
      IF(M.EQ.2)GO TO 1
      CALL VPROP(T,P,D,K,H,S,U)
      RETURN
```

```
1  R =RF(5)
   AK=RF(6)
   IF(K.EQ.1)CALL PFND(T,D,P)
   IF(K.EQ.2)CALL DFND(T,P,D,0)
   VP=VPN(T)
   CALL DFND(T,VP,DSV,2)
   CALL VPROP(T,VPP,DSV,1,HSV,SSV,USV)
   VSV=1.00/DSV
   CALL DFND(T,VP,DSL,1)
   VSL=1.00/DSL
   CALL DPDTVP(T,VP,DPDT)
   HSL=HSV-T*DPDT*(VSV-VSL)*AK
   SSL=SSV+(HSL-HSV)/T
   USL=USV+(HSL-HSV)-(VP*(VSL-VSV))*AK
   DLD=ALOG(D)
   DLS = ALOG(DSL)
   F1D=R*DLD-FING1(T,D)
   F1S=R*DLS-FING1(T,DSL)
   F2D=FING2(T,D)+R*T*DLD
   F2S=FING2(T,DSL)+R*T*DLS
   S=SSL-(F1D-F1S)*AK
   U=USL+((F2D-F2S)-T*(F1D-F1S))*AK
   H=U + (P/D)*AK
   RETURN
   END


   SUBROUTINE MQRCAL(HOT,H,D,T,W,BMACH,QN2,REY)
C  SUBROUTINE CAL  M,Q,REY/M
   VEL = SQRT(2/.0280134*(HOT-H))
   BMACH = VEL/W
   QN2 = D*28.0134*VEL**2/2.0
   DD=D*.0280134
   EMU =VISC(DD,T)*1.E-04
   REY = 28.0134*D*BMACH*W/EMU
   RETURN
   END


   SUBROUTINE MVCAL(HOT,H,W,BMACH,VEL)
   VEL = SQRT(2/.0280134*(HOT-H))
   BMACH = VEL/W
   RETURN
   END


   SUBROUTINE PFND(T,D,P)
   COMMON /RFPR/ RF(10)
   COMMON /CEOS/G(41)
   COMMON /SCRH/ B(40)
C
```

APPENDIX C

```
C.... THIS ROUTINE CALCULATES PRESSURE GIVEN TEMPERATURE AND DENSITY
C.... FROM THE EQUATION OF STATE
C
      R=RF(5)
      D2=D*D
      D3=D2*D
      D4=D3*D
      D5=D4*D
      D6=D5*D
      D7=D6*D
      D8=D7*D
      D9=D8*D
      D10=D9*D
      D11=D10*D
      D12=D11*D
      D13=D12*D
      TS=SQRT(T)
      T2=T*T
      T3=T2*T
      T4=T3*T
      GM=G(41)
      F = EXP(GM *D2)
      B( 1)=D2*T
      B( 2)=D2*TS
      B( 3)=D2
      B( 4)=D2/T
      B( 5)=D2/T2
      B( 6)=D3*T
      B( 7)=D3
      B( 8)=D3/T
      B( 9)=D3/T2
      B(10)=D4*T
      B(11)=D4
      B(12)=D4/T
      B(13)=D5
      B(14)=D6/T
      B(15)=D6/T2
      B(16)=D7/T
      B(17)=D8/T
      B(18)=D8/T2
      B(19)=D9/T2
      B(20)=D3*F/T2
      B(21)=D3*F/T3
      B(22)=D5*F/T2
      B(23)=D5*F/T4
      B(24)=D7*F/T2
      B(25)=D7*F/T3
      B(26)=D9*F/T2
      B(27)=D9*F/T4
      B(28)=D11*F/T2
      B(29)=D11*F/T3
      B(30)=D13*F/T2
      B(31)=D13*F/T3
      B(32)=D13*F/T4
      N=32
      P=0
      DO 1 I=1,N
```

```
    1 P=P+B(I)*G(I)
      P=P+R*D*T
      RETURN
      END



      SUBROUTINE PROP(T,P,D,K,H,S,U)
      COMMON /CRPR/ CR(3) /METH/M
C
C.... GENERALIZED PROPERTY CALCULATOR
C.... WRITTEN 7/20/71  A MYERS
C.... REVISED 12/10/71 A MYERS
C
C.... ROUTINE CALCULATES PROPERTIES FOR FOLLOWING INPUT OF K
C
C     K=1   INPUT IS T + P    RETURNS D, H, S, + U
C     K=2   INPUT IS T + D    RETURNS P, H, S, + U
C     K=3   INPUT IS T        RETURNS P, D, H, S, • U FOR SATURATED VAPOR
C     K=4   INPUT IS T        RETURNS P, D, H, S, • U FOR SATURATED LIQUID
C
C.... NOTE:    ALL REAL VARIABLES IN CALL STATEMENTS TO ROUTINES IN
C              THIS PACKAGE MUST BE TYPE REAL*8 (DOUBLE PRECISION)
C
C.... NOTE:    THE FIRST CALL STATEMENT IN THE USER*S MAIN PROGRAM MUST
C              BE TO A DATA INITIALIZATION ROUTINE
C              EXAMPLE:  CALL DATAN2
C
C.... NOTE:    THE METHOD OF PROPERTY CALCULATION IS DETERMINED BY THE
C              VALUE OF M CONTAINED IN COMMON BLOCK /METH/M
C
C     M=1    INDICATES PROPERTY CALCULATION TO BE CARRIED OUT BY
C            CONTINUOUS INTEGRATION OF ISOTHERMS THROUGH THE TWO PHASE
C            REGION
C     M=2    INDICATES PROPERTY CALCULATION IS INTERRUPTED AT THE TWO
C            PHASE VAPOR BOUNDARY AND THE CLAPEYRON RELATION WITH THE
C            VAPOR PRESSURE EQUATION IS USED TO CALCULATE THE LATENT
C            HEAT.  INTEGRATION OF ISOTHERMS IS CONTINUED AT THE
C            SATURATED LIQUID BOUNDARY
C
      PC=CR(1)
      DC=CR(2)
      TC=CR(3)
      IF((K.GT.0).AND.(K.LT.5))GO TO 1
      WRITE(3,300)K
  300 FORMAT(27H *** ERROR IN CALL PROP ***,/,
     .       *      K MUST EQUAL 1,2,3, OR 4*,/,
     .       *      K = *,I10)
      RETURN
    1 IF(K.LT.3)GO TO 3
      IF(T.LE.TC)GO TO 2
      WRITE(3,301)T
  301 FORMAT(27H *** ERROR IN CALL PROP ***,/,
     .       *      SATURATION PROPERTIES HAVE BEEN REQUESTED*,/,
     .       *      FOR A TEMPERATURE THAT EXCEEDS CRITICAL*,/,
     .       *      T = *,F15.5)
```

```
    2 P=VPN(T)
      IF(K.EQ.3)CALL DFND(T,P,D,2)
      IF(K.EQ.4)CALL DFND(T,P,D,1)
      GO TO 4
    3 IF(K.GT.1)GO TO 7
      CALL DFND(T,P,D,0)
      IF(T.GT.TC)GO TO 5
    4 IF(D.GT.DC)GO TO 6
    5 CALL VPROP(T,P,D,3,H,S,U)
      RETURN
    6 IF(M.EQ.1)GO TO 5
      CALL LPROP(T,P,D,3,H,S,U)
      RETURN
    7 IF(T.GT.TC)GO TO 8
      VP=VPN(T)
      CALL DFND(T,VP,DV,2)
      CALL DFND(T,VP,DL,1)
      IF(D.GE.DL)GO TO 9
      IF(D.GT.DV)GO TO 10
    8 CALL VPROP(T,P,D,1,H,S,U)
      RETURN
    9 IF(M.EQ.1)GO TO 8
      CALL LPROP(T,P,D,1,H,S,U)
      RETURN
   10 VL=1.00/DL
      VV=1.00/DV
      V =1.00/D
      X=(V-VL)/(VV-VL)
      CALL VPROP(T,P,DV,1,HV,SV,UV)
      IF(M.EQ.2)GO TO 11
      CALL VPROP(T,P,DL,1,HL,SL,UL)
      GO TO 12
   11 CALL LPROP(T,P,DL,1,HL,SL,UL)
   12 H=HL+X*(HV-HL)
      S=SL+X*(SV-SL)
      U=UL+X*(UV-UL)
      RETURN
      END



      SUBROUTINE TVP(P,T)
      COMMON /CTEVP/GT(8) /CRPR/CR(3)
      COMMON /SCRH/ X(40)
C
C.... ROUTINE TO SOLVE VAPOR PRESSURE EQUATION ITERATIVELY FOR
C.... TEMPERATURE BY NEWTON*S METHOD
C.... WRITTEN 7/22/71   A MYERS
C
C
      TC=CR(3)
C
```

```
C.... USE TEMP EXPLICIT EQN FOR FIRST APPROX
C
      P2=P*P
      P3=P2*P
      P4=P3*P
      P5=P4*P
      P6=P5*P
      X(1)=ALOG(P)
      X(2)=1.00
      X(3)=P
      X(4)=P2
      X(5)=P3
      X(6)=P4
      X(7)=P5
      X(8)=P6
      T=0
      DO 1 I=1,8
    1 T=T+X(I)*GT(I)
      T=1.00/T
C
C.... T IS NOW FIRST EST OF T
C
      ITRMAX=25
      EPS=1.E-7
      DO 2 ITER=1,ITRMAX
      PP=VPN(T)
      CALL DPDTVP(T,P,DPDT)
      DELTA=(P-PP)/DPDT
      T=T+DELTA
      IF( ABS(DELTA/T).LT.EPS)RETURN
    2 CONTINUE
      WRITE(3,300)P,T,DELTA
  300 FORMAT(25H *** TVP DID NOT CONVERGE,/,
     .      * P   =*,F15.7,
     .      * T   =*,F15.7,
     .      * DEL =*,F15.7)
      RETURN
      END


      SUBROUTINE TCHANG(BMACH,AM7,T,D,SOT,HOT)
C     THIS SUB. CHANGES TEMP ACCORDING TO TEMP VS MACH CURVE
      TUP =T+.00001*T
      TDN=T-.00001*T
      DUP=DSFND(SOT,TUP,D)
      DDN=DSFND(SOT,TDN,DUP)
      CALL PROP(TUP,PUP,DUP,2,HUP,SUP,UUP)
      CALL VSND(TUP,PUP,DUP,2,WUP)
      CALL MVCAL(HOT,HUP,WUP,UMACH,UVEL)
      CALL PROP(TDN,PDN,DDN,2,HDN,SDN,UDN)
      CALL VSND(TDN,PDN,DDN,2,WDN)
      CALL MVCAL(HOT,HDN,WDN,DMACH,DVEL)
      T=T-(BMACH-AM7)*(TUP-TDN)/(UMACH-DMACH)
      RETURN
      END
```

```
      SUBROUTINE VPROP(T,P,D,K,H,S,U)
      COMMON /RFPR/ RF(10)
C
C.... ROUTINE TO CALCULATE THE PROPERTIES OF THE VAPOR
C.... WRITTEN 7/20/71 A MYERS
C
C     K =1    INPUT IS T + D
C     K =2    INPUT IS T + P
C     K =3    INPUT IS T, P, + D
C
      IF(K.EQ.1)CALL PFND(T,D,P)
      IF(K.EQ.2)CALL DFND(T,P,D,0)
      HOTO=RF(1)
      SOTO=RF(2)
      RFST=RF(3)
      RFHT=RF(4)
      R   =RF(5)
      AK  =RF(6)
      F1D=FING1(T,D)
      F10=FING1(T,0)
      F2D=FING2(T,D)
      F20=FING2(T,0)
      SO=SOTO+CPSI(T)-CPSI(RFST)
      HO=HOTO+CPHI(T)-CPHI(RFHT)
      S=SO-(R*ALOG(D*R*T)-F1D+F10)*AK
      H=HO+(T*(F1D-F10)+F2D-F20+P/D-R*T)*AK
      U=H-(P/D)*AK
      RETURN
      END
```

```
      SUBROUTINE VSND(T,P,D,K,W)
      COMMON /RFPR/ RF(10)
C
C.... ROUTINE TO CALCULATE THE SONIC VELOCITY FOR FOLLOWING INPUT OF K
C.... WRITTEN 2/3/72 A MYERS
C
C     K =1    INPUT IS T + P   RETURNS SONIC VELOCITY, W + D
C     K =2    INPUT IS T + D   RETURNS SONIC VELOCITY, W
C     K =3    INPUT IS T       RETURNS W, D, + P FOR SATURATED VAPOR
C     K =4    INPUT IS T       RETURNS W, D, + P FOR SATURATED LIQUID
C
      AK=RF(6)
      AM=RF(7)
      IF((K.GT.0).OR.(K.LT.5))GO TO 1
      WRITE(3,300)K
  300 FORMAT(27H *** ERROR IN CALL VSND ***,/,
     .        *     K MUST EQUAL 1,2,3, OR 4*,/,
     .        *     K = *,I10)
      RETURN
    1 IF(K.EQ.2)GO TO 3
      IF(K.GT.2)GO TO 2
      CALL DFND(T,P,D,0)
      GO TO 3
    2 P=VPN(T)
      IF(K.EQ.3)CALL DFND(T,P,D,2)
      IF(K.EQ.4)CALL DFND(T,P,D,1)
```

```
    3 CALL CPVTD(T,D,CP,CV)
      W=(CP/CV)*DPDD(T,D)*(AK*1000.00/AM)
      IF(W.LE.0.   )GO TO 4
      W= SQRT(W)
      RETURN
    4 CONTINUE
      W=0
      RETURN
      END



      FUNCTION CPHI(T)
      COMMON /RFPR/ RF(10)
      COMMON /CIGCP/G(9)
      COMMON /SCRH/ X(40)
C
C.... ROUTINE TO CALCULATE INTEGRAL(CPO DT)
C
C.... WRITTEN 7/19/71
C
      R=RF(5)
      AK=RF(6)
      T2=T*T
      T3=T2*T
      T4=T3*T
      U=G(9)/T
      X(1)=-1.00/(2.00*T2)
      X(2)=-1.00/T
      X(3) = ALOG(T)
      X(4)=T
      X(5)=T2/2.00
      X(6)=T3/3.00
      X(7)=T4/4.00
      X(8) = U* T/(EXP(U) -1.0)
      CPHI=0
      DO 1 I=1,8
    1 CPHI=CPHI+X(I)*G(I)
      CPHI=CPHI*R
      CPHI=CPHI*AK
      RETURN
      END



      FUNCTION CPIG(T)
      COMMON /RFPR/ RF(10)
      COMMON /CIGCP/G(9)
      COMMON /SCRH/ X(40)
C
C.... CALCULATE IDEAL-GAS HEAT CAPACITY, CP
C
C.... WRITTEN 7/19/71 - A MYERS
```

APPENDIX C

```
C
      R=RF(5)
      AK=RF(6)
      T2=T*T
      T3=T2*T
      U=G(9)/T
      U2=U*U
      X(1)=1.00/T3
      X(2)=1.00/T2
      X(3)=1.00/T
      X(4)=1.00
      X(5)=T
      X(6)=T2
      X(7)=T3
      X(8) = U2 * EXP(U)/(EXP(U) -1.0)**2
      CPIG=0.00
      DO 1 I=1,8
    1 CPIG=CPIG+X(I)*G(I)
      CPIG=CPIG*R*AK
      RETURN
      END



      FUNCTION CPSI(T)
      COMMON /CIGCP/G(9)
      COMMON /RFPR/ RF(10)
      COMMON /SCRH/ X(40)
C
C.... ROUTINE TO CALCULATE INTEGRAL(CPO/T DT)
C
C.... WRITTEN 7/19/71 - A MYERS
C
      R=RF(5)
      AK=RF(6)
      T2=T*T
      T3=T2*T
      U=G(9)/T
      EU = EXP(U)
      X(1)=-1.00/(3.00*T3)
      X(2)=-1.00/(2.00*T2)
      X(3)=-1.00/T
      X(4)=ALOG(T)
      X(5)=T
      X(6)=T2/2.00
      X(7)=T3/3.00
      X(8)=U/(EU-1.00)-ALOG(1.00-1.00/EU)
      CPSI=0
      DO 1 I=1,8
    1 CPSI=CPSI+X(I)*G(I)
      CPSI=CPSI*R
      CPSI=CPSI*AK
      RETURN
      END
```

APPENDIX C

```
      FUNCTION DELC(DD,TT)
C     SET UP FOR NITROGEN
C     INPUT, TEMP=K,  DENSITY=GM/CC
C     OUTPUT, MW/CM-K
      TYPE REAL K
      DATA(AV=6.025E+23),(K=1.38054E-16),(F1=100.),(EM=28.016),(EOVERK=
     1118.0),(RM=3.933E-08),(X=1.6711),(TC=126.26),(DC=0.31406)
      DATA(IND=1)
      IF(IND.GT.1) GO TO 1
      C1=K**0.5/(6.*3.14159*(AV/EM)**0.5)
      R1=RM**2.5*(AV/EM)**0.5*EOVERK**0.5*X
      DF1=1000./EM
      DF2=1.0
      IND=2
    1 R=R1*DD**0.5/TT**0.5
      ETA=VISC(DD,TT)/1000.
      BTT=((TT-TC)/TC)**2
      BDD=((DD-DC)/DC)**4
      T=TT
C     CONVERTS DENSITIES TO MOLES / LITER FOR COMPUTATION OF DERIVATIVES
      DMOLES=DD*DF1
      DPT=DPDT(TT,DMOLES)*DF2*1.01325E+6
      DPD=DPDD(TT,DMOLES)*DF1*1.01325E+6
      DELC02=C1*T**1.5*DPT**2/(R*ETA*DD*DPD**0.5)/F1
      DELC=DELC02 * EXP(-18.66 * BTT -4.25 * BDD)
      DELC=DELC/100.
      RETURN
      END


      FUNCTION DPDD(T,D)
      COMMON /RFPR/ RF(10)
      COMMON /CEOS/G(41)
      COMMON /SCRH/ X(40)
C
C.... CALCULATES DP/DD OF THE EQUATION OF STATE
C
      P=RF(5)
      D2=D*D
      D3=D2*D
      D4=D3*D
      D5=D4*D
      D6=D5*D
      D7=D6*D
      D8=D7*D
      D9=D8*D
      D10=D9*D
      D11=D10*D
      D12=D11*D
      D13=D12*D
      TS=SQRT(T)
      T2=T*T
      T3=T2*T
      T4=T3*T
      GM=G(41)
```

```
      F = EXP(GM *D2)
      F1=2.00*F*GM*D
      F21=3.000*F*D2 +F1*D3
      F22=5.000*F*D4 +F1*D5
      F23=7.000*F*D6 +F1*D7
      F24=9.000*F*D8 +F1*D9
      F25=11.00*F*D10+F1*D11
      F26=13.00*F*D12+F1*D13
      X( 1)=2.00*D*T
      X( 2)=2.00*D*TS
      X( 3)=2.00*D
      X( 4)=2.00*D/T
      X( 5)=2.00*D/T2
      X( 6)=3.00*D2*T
      X( 7)=3.00*D2
      X( 8)=3.00*D2/T
      X( 9)=3.00*D2/T2
      X(10)=4.00*D3*T
      X(11)=4.00*D3
      X(12)=4.00*D3/T
      X(13)=5.00*D4
      X(14)=6.00*D5/T
      X(15)=6.00*D5/T2
      X(16)=7.00*D6/T
      X(17)=8.00*D7/T
      X(18)=8.00*D7/T2
      X(19)=9.00*D8/T2
      X(20)=F21/T2
      X(21)=F21/T3
      X(22)=F22/T2
      X(23)=F22/T4
      X(24)=F23/T2
      X(25)=F23/T3
      X(26)=F24/T2
      X(27)=F24/T4
      X(28)=F25/T2
      X(29)=F25/T3
      X(30)=F26/T2
      X(31)=F26/T3
      X(32)=F26/T4
      N=32
      DPDD=0
      DO 1 K=1,N
    1 DPDD=DPDD+X(K)*G(K)
      DPDD=DPDD+R*T
      RETURN
      END


      FUNCTION DPDT(T,D)
      COMMON /CEOS/G(41)
      COMMON /RFPR/ PF(10)
      COMMON /SCRH/ X(40)
```

APPENDIX C

```
C
C.... CALCULATES DP/DT OF THE EQUATION OF STATE
C
      R=RF(5)
      D2=D*D
      D3=D2*D
      D4=D3*D
      D5=D4*D
      D6=D5*D
      D7=D6*D
      D8=D7*D
      D9=D8*D
      D10=D9*D
      D11=D10*D
      D12=D11*D
      D13=D12*D
      TS=SQRT(T)
      T2=T*T
      T3=T2*T
      T4=T3*T
      T5=T4*T
      GM=G(41)
      F = EXP(GM *D2)
      X( 1)=D2
      X( 2)=D2/(2.00*TS)
      X( 3)=0
      X( 4)=-D2/T2
      X( 5)=-2.00*D2/T3
      X( 6)=D3
      X( 7)=0
      X( 8)=-D3/T2
      X( 9)=-2.00*D3/T3
      X(10)=D4
      X(11)=0
      X(12)=-D4/T2
      X(13)=0
      X(14)=-D6/T2
      X(15)=-2.00*D6/T3
      X(16)=-D7/T2
      X(17)=-D8/T2
      X(18)=-2.00*D8/T3
      X(19)=-2.00*D9/T3
      X(20)=-2.00*D3*F/T3
      X(21)=-3.00*D3*F/T4
      X(22)=-2.00*D5*F/T3
      X(23)=-4.00*D5*F/T5
      X(24)=-2.00*D7*F/T3
      X(25)=-3.00*D7*F/T4
      X(26)=-2.00*D9*F/T3
      X(27)=-4.00*D9*F/T5
      X(28)=-2.00*D11*F/T3
      X(29)=-3.00*D11*F/T4
      X(30)=-2.00*D13*F/T3
      X(31)=-3.00*D13*F/T4
      X(32)=-4.00*D13*F/T5
```

APPENDIX C

```
      N=32
      DPDT=0
      DO 1 K=1,N
    1 DPDT=DPDT+X(K)*G(K)
      DPDT=DPDT+R*D
      RETURN
      END



      FUNCTION DSATL(T)
      COMMON /CRPR/CR(3) /CSL/G(7)
      COMMON /SCRH/ B(40)
C
C.... THIS FUNCTION SUPPLIES AN APPROXIMATE VALUE FOR THE
C.... DENSITY OF THE SATURATED LIQUID
C
C.... WRITTEN 9/20/71 A MYERS
C
      TC=CR(3)
      X=(TC-T)/TC
      X2=X*X
      X3=X*X2
      X4=X*X3
      X5=X*X4
      B(1)=1.00
      B(2)=X
      B(3)=X2
      B(4)=X3
      B(5)=X4
      B(6)=X5
      B(7)=ALOG(X)
      DSL=0
      DO 1 I=1,7
    1 DSL=DSL+B(I)*G(I)
      DSATL=DSL
      RETURN
      END



      FUNCTION DSATV(T)
      COMMON /CRPR/CR(3) /CSV/G(7)
      COMMON /SCRH/ B(40)
C
C.... THIS FUNCTION SUPPLIES AN APPROXIMATE VALUE FOR THE
C.... DENSITY OF THE SATURATED VAPOR
C
C.... WRITTEN 9/20/71 A MYERS
C
      TC=CR(3)
      X=(TC-T)/TC
      X2=X*X
      X3=X*X2
      X4=X*X3
      X5=X*X4
```

```
      B(1)=1.00
      B(2)=X
      B(3)=X2
      B(4)=X3
      B(5)=X4
      B(6)=X5
      B(7)=ALOG(X)
      DSV=0
      DO 1 I=1,7
    1 DSV=DSV+B(I)*G(I)
      DSV = EXP(DSV)
      DSATV=DSV
      RETURN
      END


      FUNCTION DSFND(SOT,TT,DD)
      T=TT
      D=DD
      DO 10 I=1,100
      CALL PROP(T,P,D,2,H,S,U)
      IF(ABS(S-SOT)-1.E-07*SOT)11,11,1
    1 DUP=D+.001*D
      DDN=D-.001*D
      CALL PROP(T,P,DUP,2,H,SUP,U)
      CALL PROP(T,P,DDN,2,H,SDN,U)
      D=D-(S-SOT)/((SUP-SDN)/(DUP-DDN))
   10 CONTINUE
      D=0
   11 DSFND=D
      RETURN
      END


      FUNCTION FING1(T,D)
      COMMON/CEOS/G(41)
      COMMON /SCRH/ X(40)
C
C.... ROUTINE TO CALCULATE INTEGRAL((R/D-1/D**2(DP/DT)) DD)
C
C.... WRITTEN 7/18/71 A MYERS
C
      D2=D*D
      D3=D2*D
      D4=D3*D
      D5=D4*D
      D6=D5*D
      D7=D6*D
      D8=D7*D
      D9=D8*D
      D10=D9*D
```

```
      TS=SQRT(T)
      T2=T*T
      T3=T2*T
      T4=T3*T
      T5=T4*T
      GM=G(41)
      F = EXP(GM *D2)
      G1=F/(2.00*GM)
      G2=(F*D2-2.00*G1)/(2.00*GM)
      G3=(F*D4-4.00*G2)/(2.00*GM)
      G4=(F*D6-6.00*G3)/(2.00*GM)
      G5=(F*D8-8.00*G4)/(2.00*GM)
      G6=(F*D10-10.00*G5)/(2.00*GM)
      X( 1)=-D
      X( 2)=-D/(2.00*TS)
      X( 3)=0
      X( 4)=+D/T2
      X( 5)=2.00*D/T3
      X( 6)=-D2/2.00
      X( 7)=0
      X( 8)=D2/(2.00*T2)
      X( 9)=D2/T3
      X(10)=-D3/3.00
      X(11)=0.
      X(12)=D3/(3.00*T2)
      X(13)=0
      X(14)=D5/(5.00*T2)
      X(15)= 2.00*D5/(5.00*T3)
      X(16)=D6/(6.00*T2)
      X(17)=D7/(7.00*T2)
      X(18)=2.00*D7/(7.00*T3)
      X(19)=D8/(4.00*T3)
      X(20)=2.00*G1/T3
      X(21)=3.00*G1/T4
      X(22)=2.00*G2/T3
      X(23)=4.00*G2/T5
      X(24)=2.00*G3/T3
      X(25)=3.00*G3/T4
      X(26)=2.00*G4/T3
      X(27)=4.00*G4/T5
      X(28)=2.00*G5/T3
      X(29)=3.00*G5/T4
      X(30)=2.00*G6/T3
      X(31)=3.00*G6/T4
      X(32)=4.00*G6/T5
      FING1=0
      DO 1 I=1,32
    1 FING1=FING1+G(I)*X(I)
      RETURN
      END


      FUNCTION FING2(T,D)
      COMMON/CEOS/G(41)
      COMMON /SCRH/ X(40)
```

APPENDIX C

```
C
C.... ROUTINE TO CALCULATE INTEGRAL((P/D**2-RT/D) DD)
C
C.... WRITTEN 7/18/71 - A MYERS
C
      D2=D*D
      D3=D2*D
      D4=D3*D
      D5=D4*D
      D6=D5*D
      D7=D6*D
      D8=D7*D
      D9=D8*D
      D10=D9*D
      TS=SQRT(T)
      T2=T*T
      T3=T2*T
      T4=T3*T
      T5=T4*T
      GM=G(41)
      F = EXP(GM *D2)
      G1=F/(2.00*GM)
      G2=(F*D2-2.00*G1)/(2.00*GM)
      G3=(F*D4-4.00*G2)/(2.00*GM)
      G4=(F*D6-6.00*G3)/(2.00*GM)
      G5=(F*D8-8.00*G4)/(2.00*GM)
      G6=(F*D10-10.00*G5)/(2.00*GM)
      X( 1)=D*T
      X( 2)=D*TS
      X( 3)=D
      X( 4)=D/T
      X( 5)=D/T2
      X( 6)=D2*T/2.00
      X( 7)=D2/2.00
      X( 8)=D2/(2.00*T)
      X( 9)=D2/(2.00*T2)
      X(10)=D3*T/3.00
      X(11)=D3/3.00
      X(12)=D3/(3.00*T)
      X(13)=D4/4.00
      X(14)=D5/(5.00*T)
      X(15)=D5/(5.00*T2)
      X(16)=D6/(6.00*T)
      X(17)=D7/(7.00*T)
      X(18)=D7/(7.00*T2)
      X(19)=D8/(8.00*T2)
      X(20)=G1/T2
      X(21)=G1/T3
      X(22)=G2/T2
      X(23)=G2/T4
      X(24)=G3/T2
      X(25)=G3/T3
      X(26)=G4/T2
      X(27)=G4/T4
      X(28)=G5/T2
      X(29)=G5/T3
      X(30)=G6/T2
      X(31)=G6/T3
      X(32)=G6/T4
```

APPENDIX C

```
      FING2=0
      DO 1 I=1,32
    1 FING2=FING2+G(I)*X(I)
      RETURN
      END

      FUNCTION FING3(T,D)
      COMMON/CEOS/G(41)
      COMMON /SCRH/ X(40)
C
C.... ROUTINE TO CALCULATE INTEGRAL((T/D**2)*(D2P/DT2) DD)
C
C.... WRITTEN 7/16/71 - A MYERS
C
      D2=D*D
      D3=D2*D
      D4=D3*D
      D5=D4*D
      D6=D5*D
      D7=D6*D
      D8=D7*D
      D9=D8*D
      D10=D9*D
      TS=SQRT(T)
      T2=T*T
      T3=T2*T
      T4=T3*T
      T5=T4*T
      GM=G(41)
      F = EXP(GM *D2)
      G1=F/(2.00*GM)
      G2=(F*D2-2.00*G1)/(2.00*GM)
      G3=(F*D4-4.00*G2)/(2.00*GM)
      G4=(F*D6-6.00*G3)/(2.00*GM)
      G5=(F*D8-8.00*G4)/(2.00*GM)
      G6=(F*D10-10.00*G5)/(2.00*GM)
      X( 1)=0
      X( 2)=-D/(4.00*TS)
      X( 3)=0
      X( 4)=2.00*D/T2
      X( 5)=6.00*D/T3
      X( 6)=0
      X( 7)=0
      X( 8)=D2/T2
      X( 9)=3.00*D2/T3
      X(10)=0
      X(11)=0
      X(12)=(2.00*D3)/(3.00*T2)
      X(13)=0
      X(14)=(2.00*D5)/(5.00*T2)
      X(15)=(6.00*D5)/(5.00*T3)
      X(16)=D6/(3.00*T2)
      X(17)=(2.00*D7)/(7.00*T2)
      X(18)=(6.00*D7)/(7.00*T3)
      X(19)=(3.00*D8)/(4.00*T3)
      X(20)=6.000*G1/T3
      X(21)=12.00*G1/T4
```

```
      X(22)=6.000*G2/T3
      X(23)=20.00*G2/T5
      X(24)=6.000*G3/T3
      X(25)=12.00*G3/T4
      X(26)=6.000*G4/T3
      X(27)=20.00*G4/T5
      X(28)=6.000*G5/T3
      X(29)=12.00*G5/T4
      X(30)=6.000*G6/T3
      X(31)=12.00*G6/T4
      X(32)=20.00*G6/T5
      FING3=0
      DO 1 I=1,32
    1 FING3=FING3+G(I)*X(I)
      RETURN
      END
```

```
      FUNCTION VISC(DD,TT)
      DIMENSION Z(18),X(11)
      DATA(  Z  =  -6.8939127475E+01   ,  3.5226118983E+00   ,
     C   -6.8357539823E-02   ,  1.5832717315E-03   ,  -2.6418423047E-06   ,
     C    3.6093309138E-09   , -2.5555598476E-12   ,   8.5635041641E-16   ,
     C   -1.0717599406E-19   ,  7.4165322904E+01   ,  -1.5834400475E+00   ,
     C    3.8530771011E-03   ,  8.0133713668E-04   ,  -8.9203123846E-07   ,
     C    8.9059711315E-10   ,  -5.3779372664E-13   ,   1.7398277309E-16   ,
     C   -2.3084044942E-20   )
      DATA(X=2.3083514362E-1,-9.3636207171E-1,9.0339186452E+0,-4.1832067
     1163E+1,1.0897627893E+2,-1.2913856376E+2,5.9782049913E+1)
      J = 9   $   K = 2
      GO TO 100
      ENTRY THERM
      J = 0   $   K = 1
100   CONTINUE
      VISC = 0    $    T = TT   $   D = DD
      DO 200 I = 1 , 9
        VISC = VISC + T**(I-3)*Z(I+J)
200   CONTINUE
      GO TO (300,400),K
300   CONTINUE
      VISC = VISC + .21959022190 * D + .063873706990*(EXP(3.6*D) - 1. )
      RETURN
400   CONTINUE
      IF(D.GT.0.8) GO TO 501
      DO 500 I=1,7
        VISC = VISC + X(I) * D**I
500   CONTINUE
      RETURN
  501 VISC=VISC-2.5781990818E+3+9.4784808659E+3*D-1.1622926973E+4*D**2+
     14.756948538E+3*D**3
C     INPUT D=GM/CC,  T=DEG K
C     OUTPUT ETA=MILI GM/CM-SEC  LAMBDA=MW/CM-K
      RETURN
      END
```

APPENDIX C

```
      FUNCTION VPN(T)
      COMMON/CVPN/G(11) /CRPR/CR(3)
      COMMON /SCRH/ X(40)
C
C.... CALCULATE THE VAPOR PRESSURE
C
C.... WRITTEN 7/22/71 A MYERS
C
      TC=CR(3)
      A=G(11)
      T2=T*T
      T3=T*T2
      T4=T*T3
      T5=T*T4
      T6=T*T5
      X(1)=1.00/T
      X(2)=1.00
      X(3)=T
      X(4)=T2
      X(5)=T3
      X(6)=T4
      X(7)=T5
      X(8)=T6
      X(9)=ALOG(T)
      X(10)=(TC-T)**A
      P=0
      DO 1 I=1,10
    1 P=P+X(I)*G(I)
      P=EXP(P)
      VPN=P
      RETURN
      END
```

Sample Output

ENERGY AND POWER REQUIREMENTS FOR FAN-DRIVEN CRYOGENIC WIND-TUNNEL
ISENTROPIC COMPRESSION IN NITROGEN

```
TEST-SECTION MACH NUMBER = 1.20
FAN PRESSURE RATIO       = 1.2000
FAN PRESSURE, OUTLET     = 5.0000 ATM
FAN PRESSURE, INLET      = 4.1667 ATM

E = FAN ENERGY
P = FAN POWER
```

	REAL GAS				IDEAL GAS				REAL/IDEAL VALUES		
TT,IN K	TT,OUT K	MDOT KGM/S-M2	E/MASS J/KGM	P/AREA J/S-M2	TT,OUT K	MDOT KGM/S-M2	E/MASS J/KGM	P/AREA J/S-M2	MDOT	E/MASS	P/AREA
294.2	310.0	1145.5	16332.7	.1871E+08	309.9	1143.8	16341.6	.1869E+08	1.0015	.9995	1.0010
284.7	300.0	1164.7	15799.5	.1840E+08	299.9	1162.7	15814.1	.1839E+08	1.0017	.9991	1.0008
275.2	290.0	1184.9	15265.9	.1809E+08	289.9	1182.6	15286.7	.1808E+08	1.0020	.9986	1.0006
265.7	280.0	1206.2	14731.7	.1777E+08	279.9	1203.5	14759.2	.1776E+08	1.0022	.9981	1.0004
256.2	270.0	1228.7	14197.0	.1744E+08	269.9	1225.6	14231.8	.1744E+08	1.0025	.9976	1.0001
246.7	260.0	1252.6	13661.5	.1711E+08	259.9	1249.0	13704.4	.1712E+08	1.0029	.9969	.9997
237.2	250.0	1277.9	13125.3	.1677E+08	249.9	1273.7	13176.9	.1678E+08	1.0033	.9961	.9993
227.7	240.0	1304.9	12588.2	.1643E+08	239.9	1300.0	12649.5	.1644E+08	1.0037	.9952	.9989
218.2	230.0	1333.7	12050.1	.1607E+08	229.9	1328.0	12122.1	.1610E+08	1.0043	.9941	.9983
208.8	220.0	1364.5	11510.7	.1571E+08	219.9	1357.9	11594.6	.1574E+08	1.0049	.9928	.9976
199.3	210.0	1397.7	10969.9	.1533E+08	209.9	1389.8	11067.1	.1538E+08	1.0056	.9912	.9968
189.8	200.0	1433.5	10427.5	.1495E+08	199.9	1424.2	10539.6	.1501E+08	1.0065	.9894	.9958
180.3	190.0	1472.3	9883.0	.1455E+08	189.9	1461.2	10012.1	.1463E+08	1.0076	.9871	.9946
170.8	180.0	1514.7	9336.0	.1414E+08	179.9	1501.3	9484.6	.1424E+08	1.0089	.9843	.9931
161.3	170.0	1561.1	8786.1	.1372E+08	169.9	1544.9	8957.0	.1384E+08	1.0105	.9809	.9912
151.8	160.0	1612.5	8232.3	.1327E+08	159.9	1592.5	8429.5	.1342E+08	1.0125	.9766	.9889
142.3	150.0	1669.7	7673.7	.1281E+08	149.9	1644.8	7901.9	.1300E+08	1.0151	.9711	.9858
132.8	140.0	1734.2	7108.6	.1233E+08	139.9	1702.7	7374.2	.1256E+08	1.0185	.9640	.9818
123.3	130.0	1807.8	6534.8	.1181E+08	129.9	1767.0	6846.6	.1210E+08	1.0231	.9545	.9765
113.8	120.0	1893.5	5948.5	.1126E+08	119.8	1839.3	6318.9	.1162E+08	1.0294	.9414	.9691
109.0	115.0	1942.2	5648.9	.1097E+08	114.8	1879.0	6055.1	.1138E+08	1.0336	.9329	.9643
104.3	110.0	1995.8	5343.4	.1066E+08	109.8	1921.3	5791.2	.1113E+08	1.0388	.9227	.9584
99.5	105.0	2055.5	5030.5	.1034E+08	104.8	1966.6	5527.4	.1087E+08	1.0452	.9101	.9512

SATURATION CONDITIONS REACHED AT THROAT MACH NUMBER

Output variables: TT,IN, stagnation temperature at fan inlet, K; TT,OUT, stagnation temperature at fan outlet, K; MDOT, mass-flow rate per unit throat area, kgm/sec-m^2; E/MASS, fan energy per unit mass of flow, J/kgm; P/AREA, fan power per unit throat area, J/sec-m^2.

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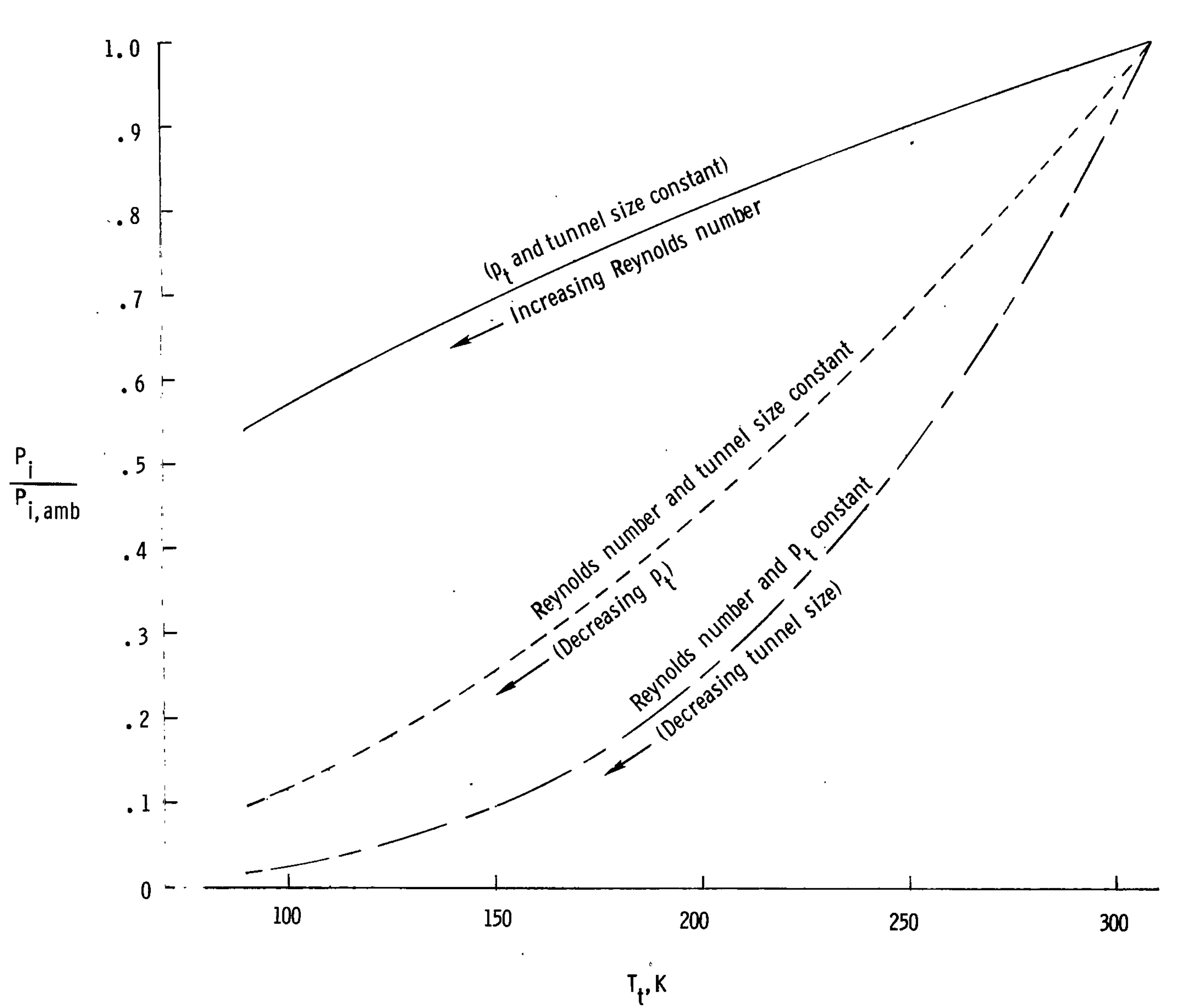


Figure 1.- Variation of tunnel drive power with tunnel operating temperature. M_{TS} = 1.0.

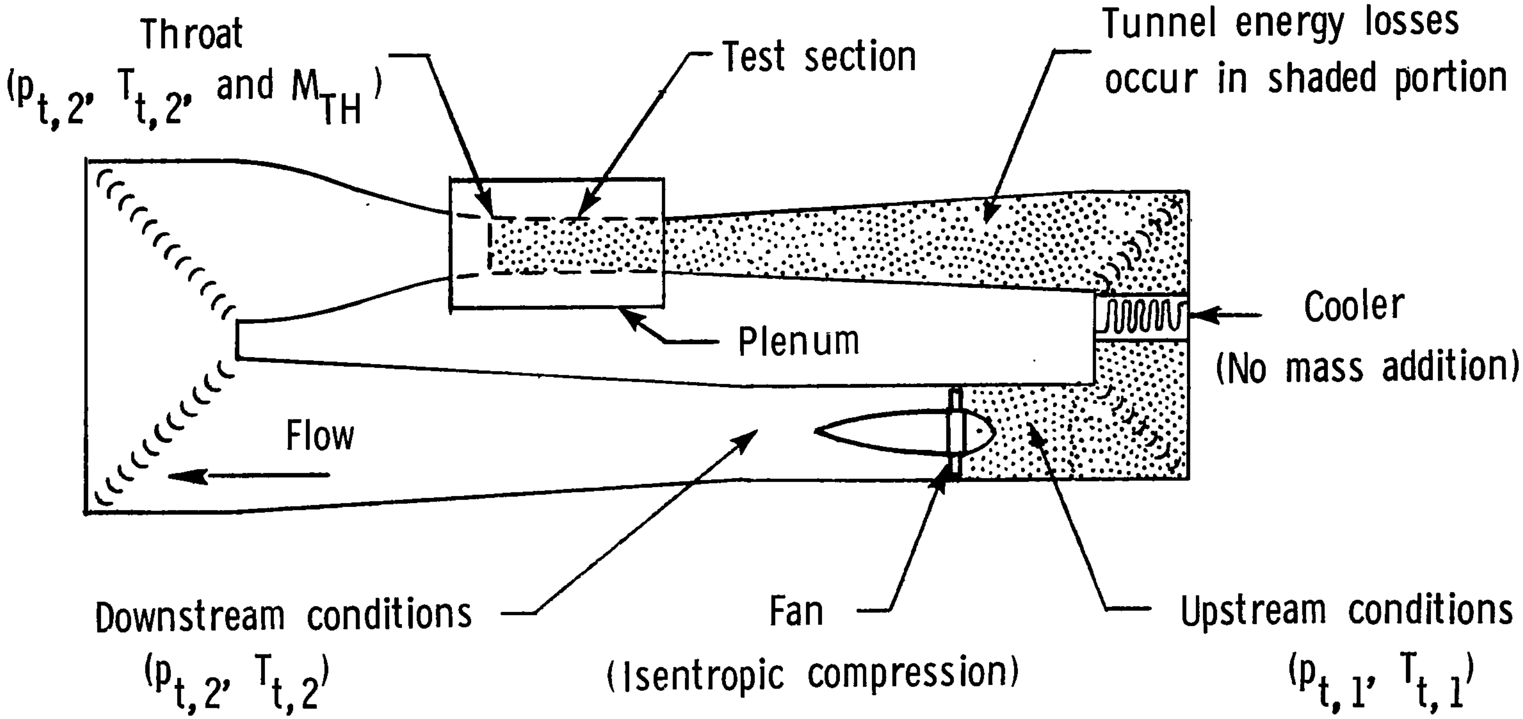


Figure 2.- Analytical model of tunnel.

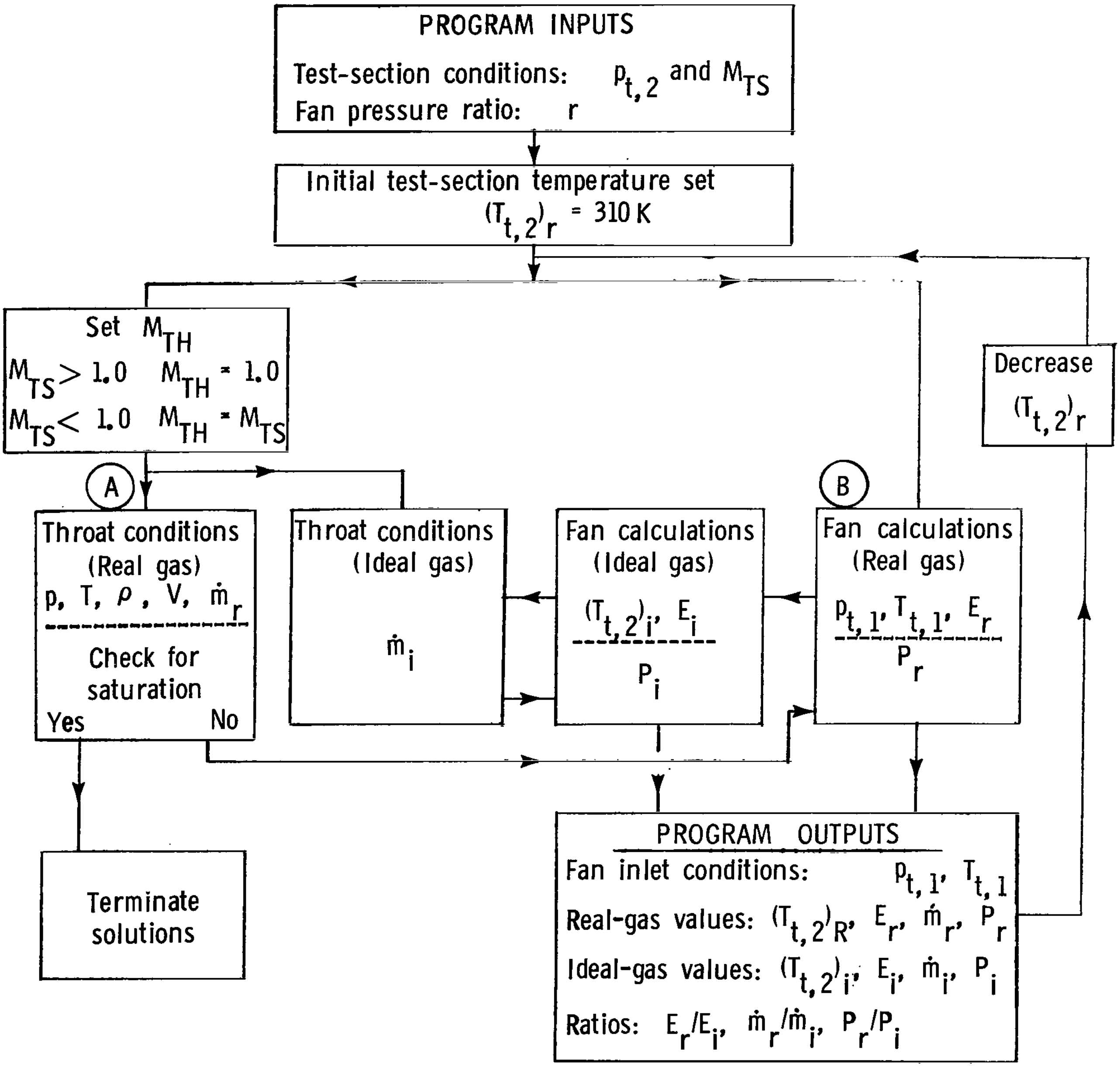


Figure 3.- Flow chart for isentropic power requirements program.

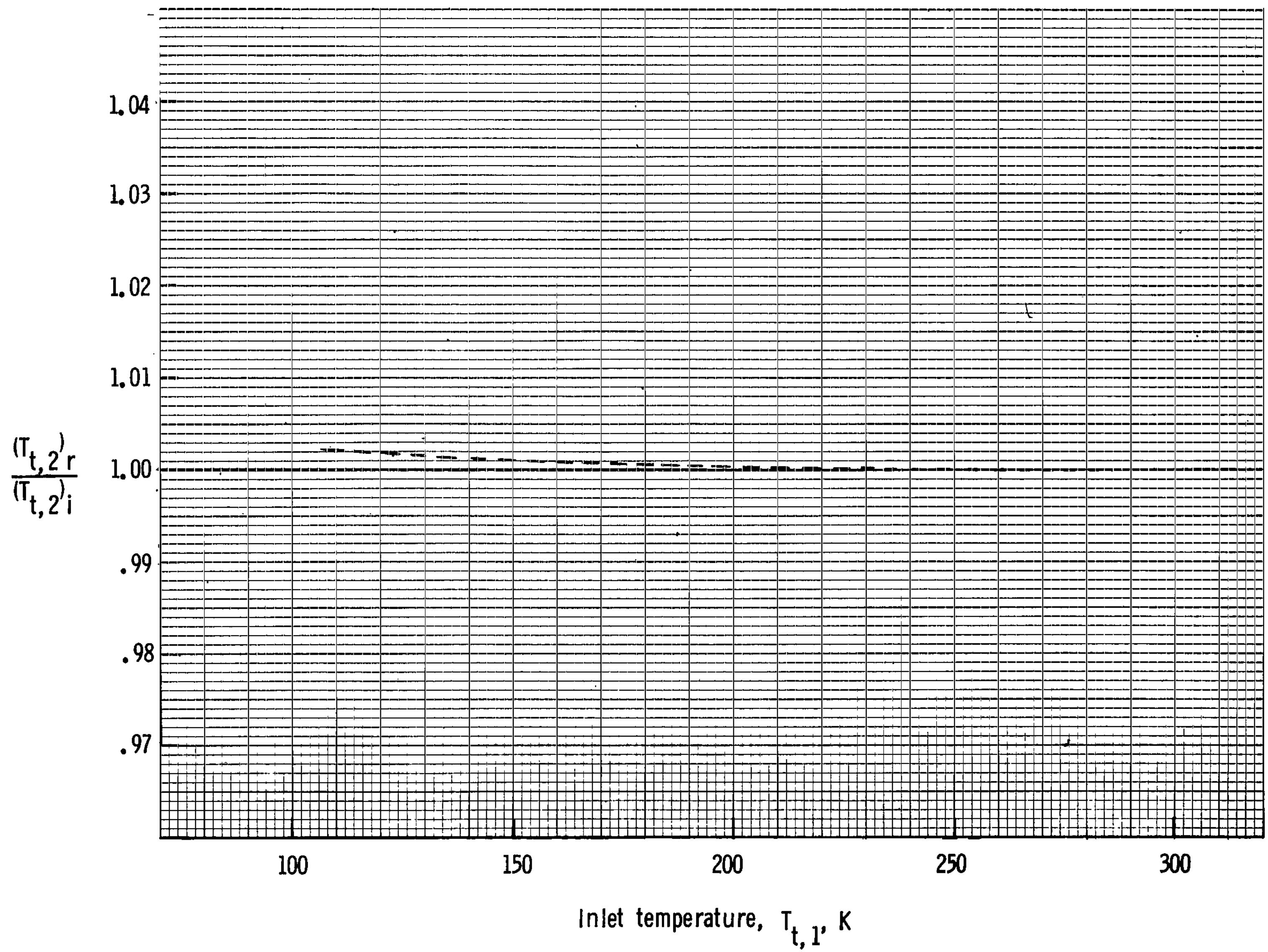
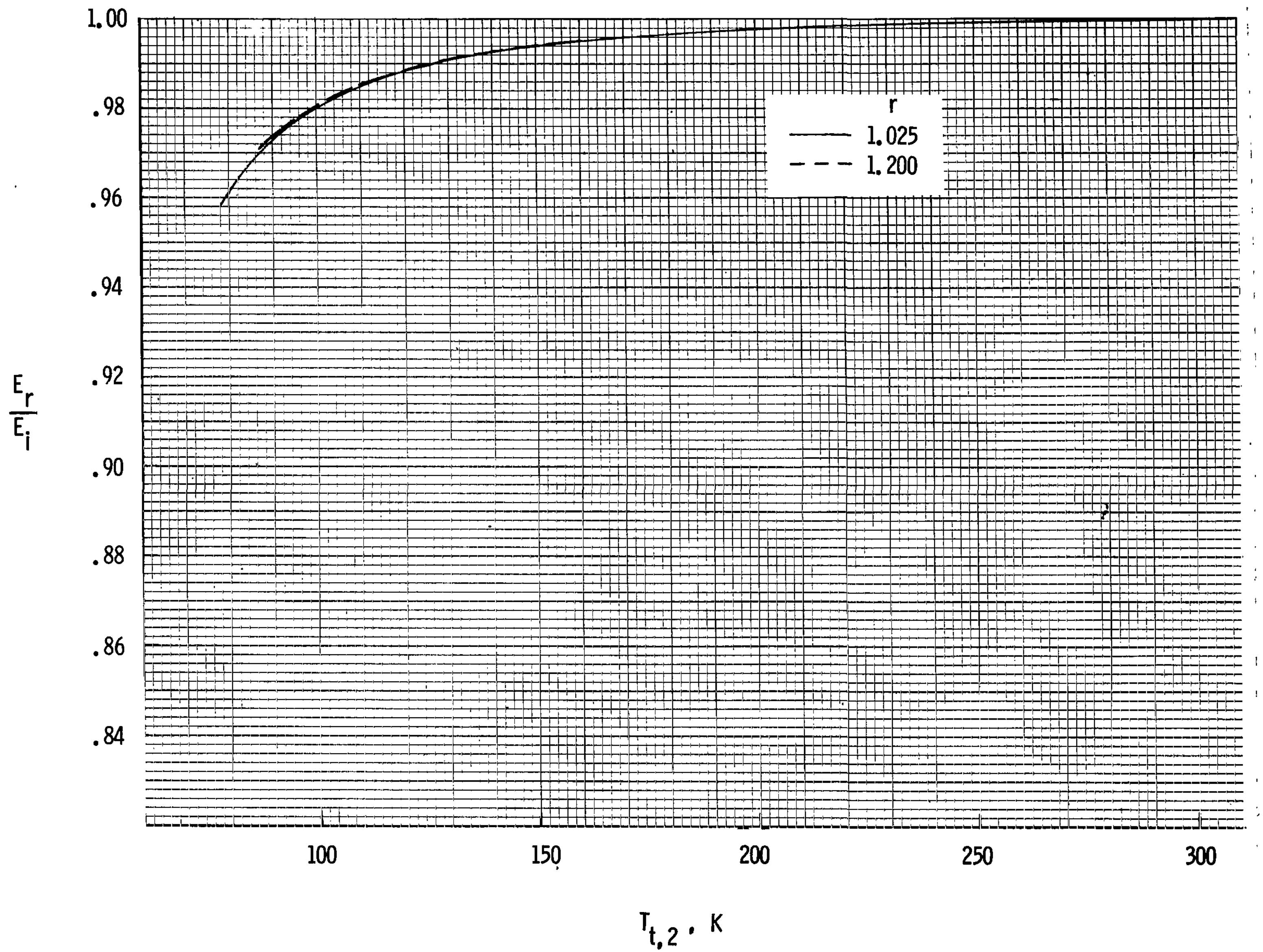
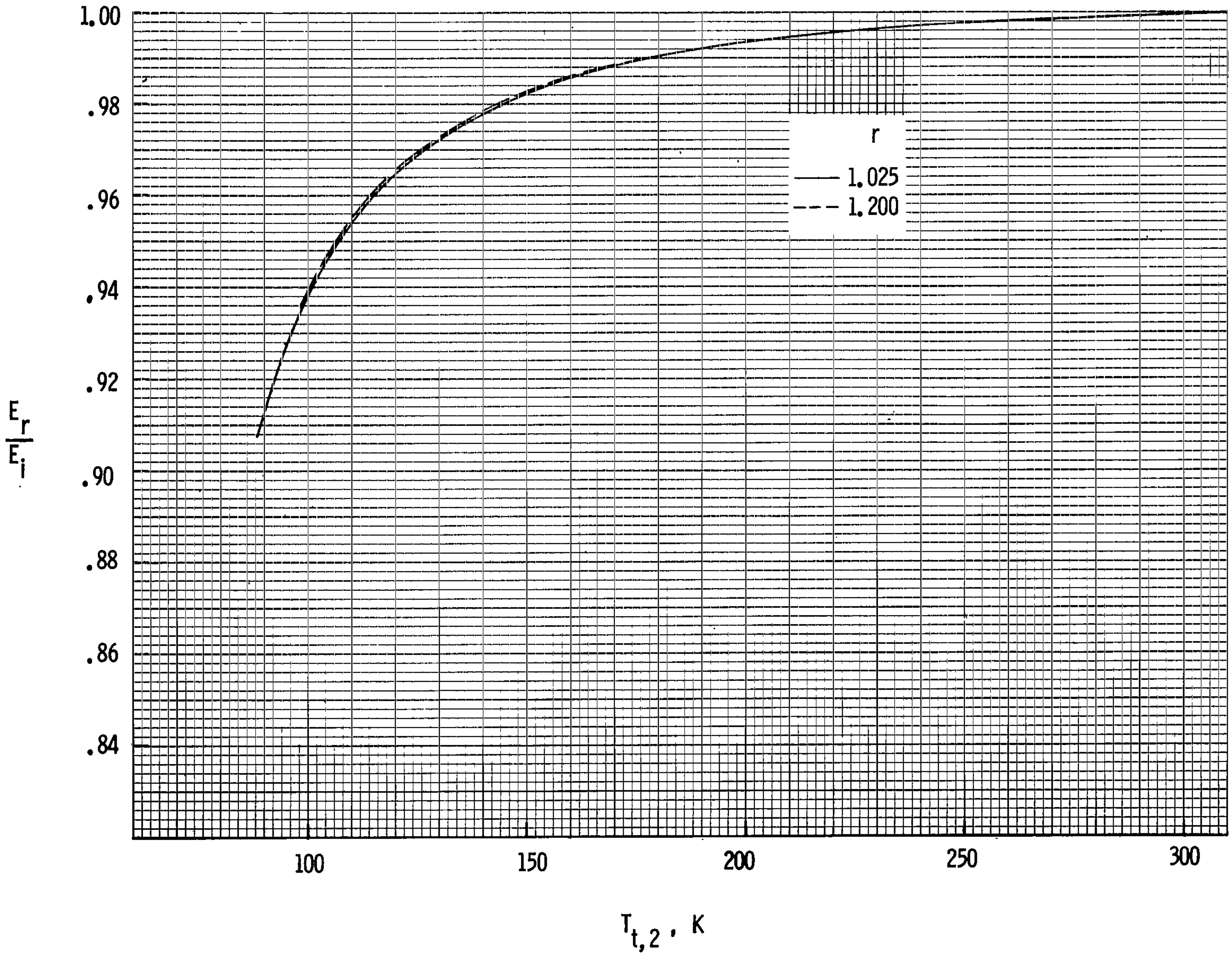


Figure 4.- Relative value of downstream stagnation temperature as function of inlet stagnation temperature. $p_{t,2} = 8.8$ atm and $r = 1.20$.



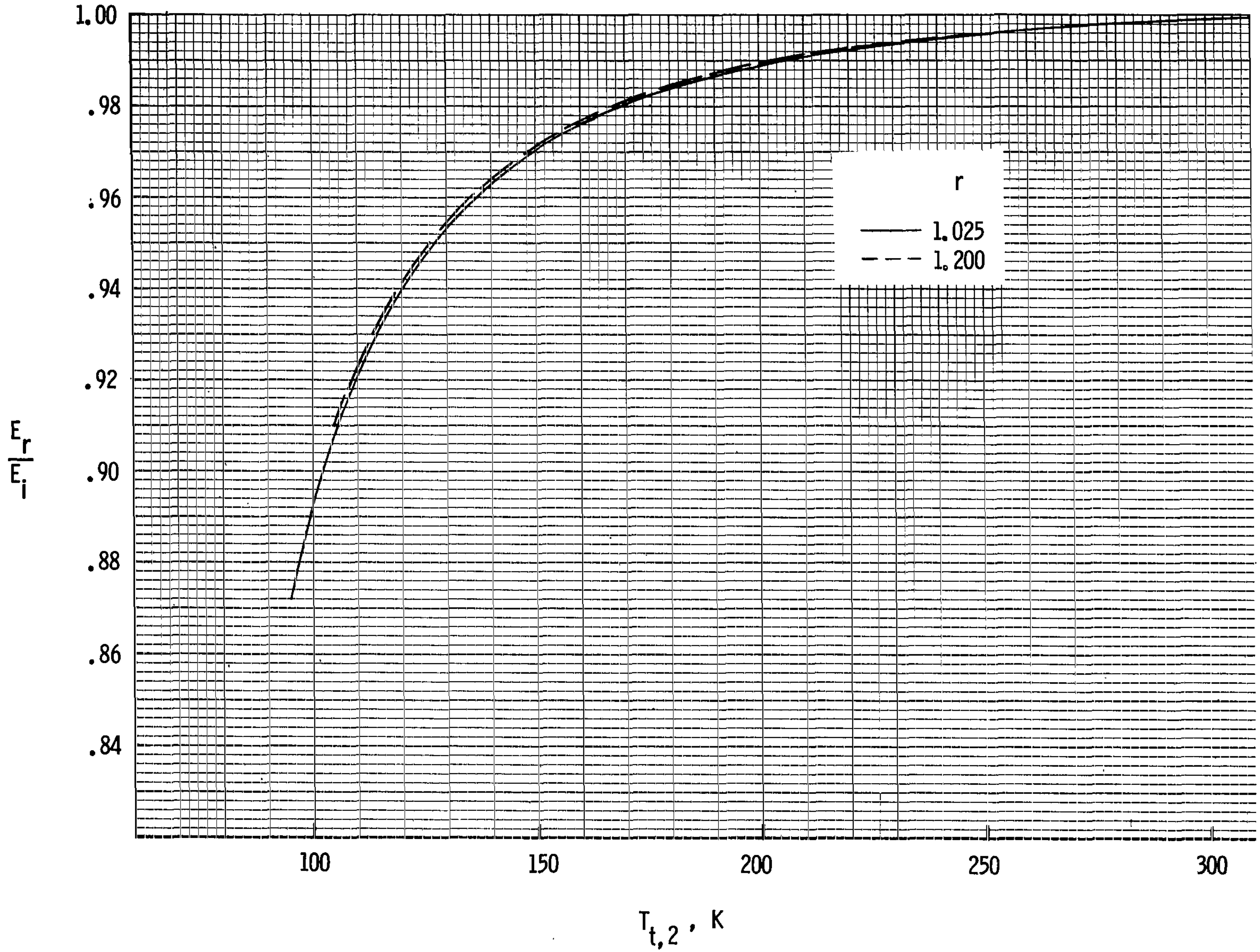
(a) $p_{t,2}$ = 1.0 atm.

Figure 5.- Energy for isentropic compressions of nitrogen (relative to ideal-gas values).



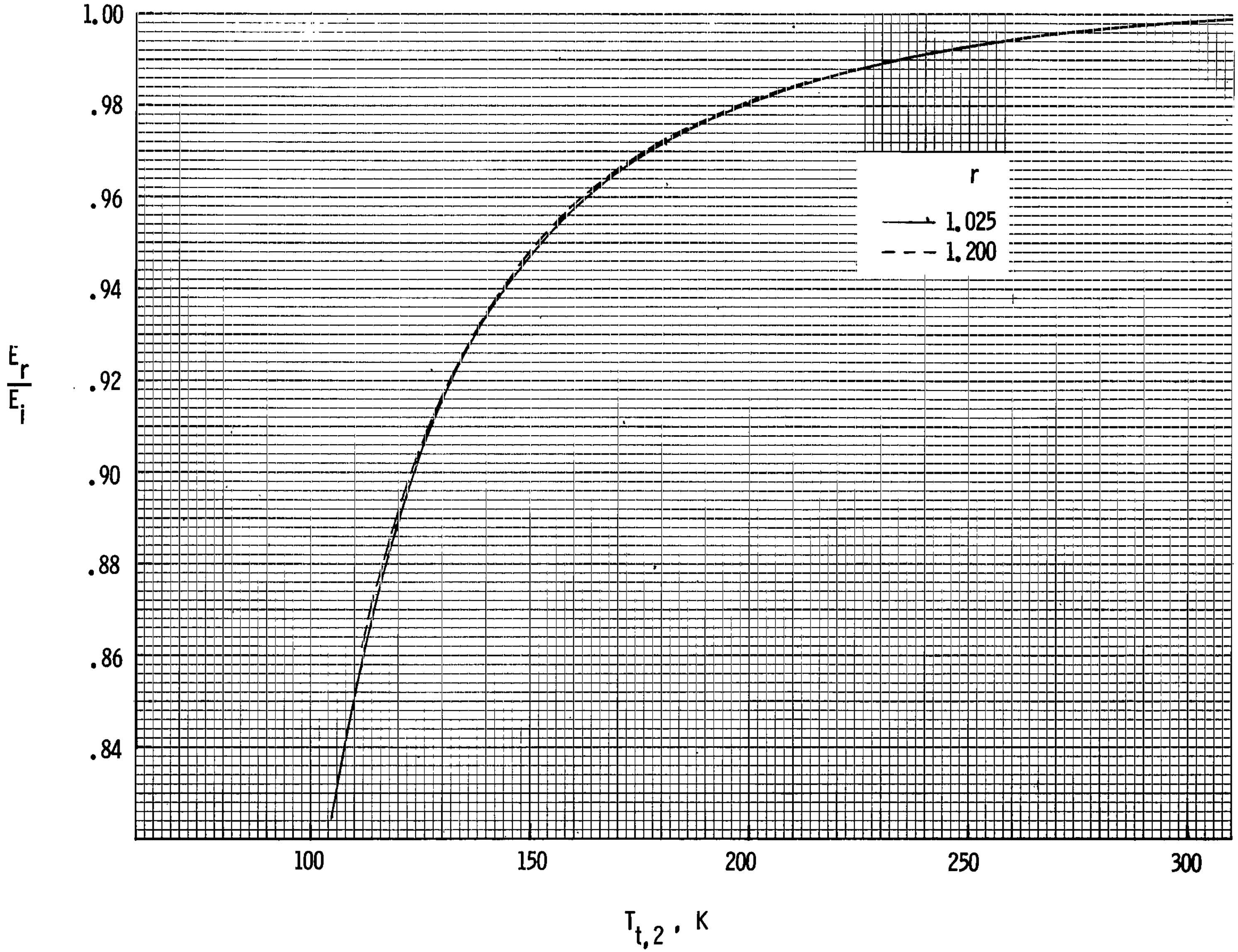
(b) $p_{t,2}$ = 3.0 atm.

Figure 5.- Continued.



(c) $p_{t,2}$ = 5.0 atm.

Figure 5.- Continued.



(d) $p_{t,2}$ = 8.8 atm.

Figure 5.- Concluded.

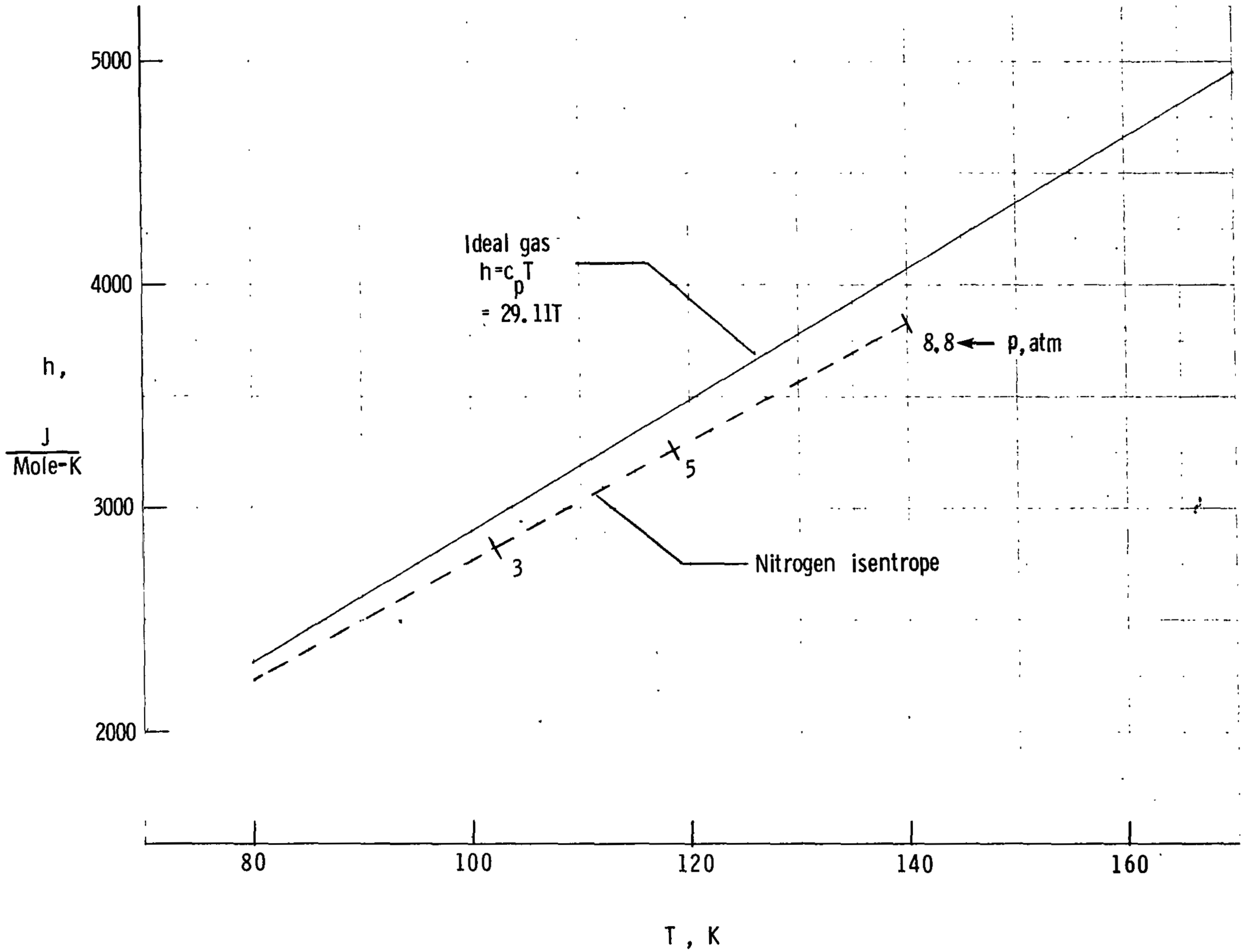


Figure 6.- Variation of enthalpy with temperature along isentropes.

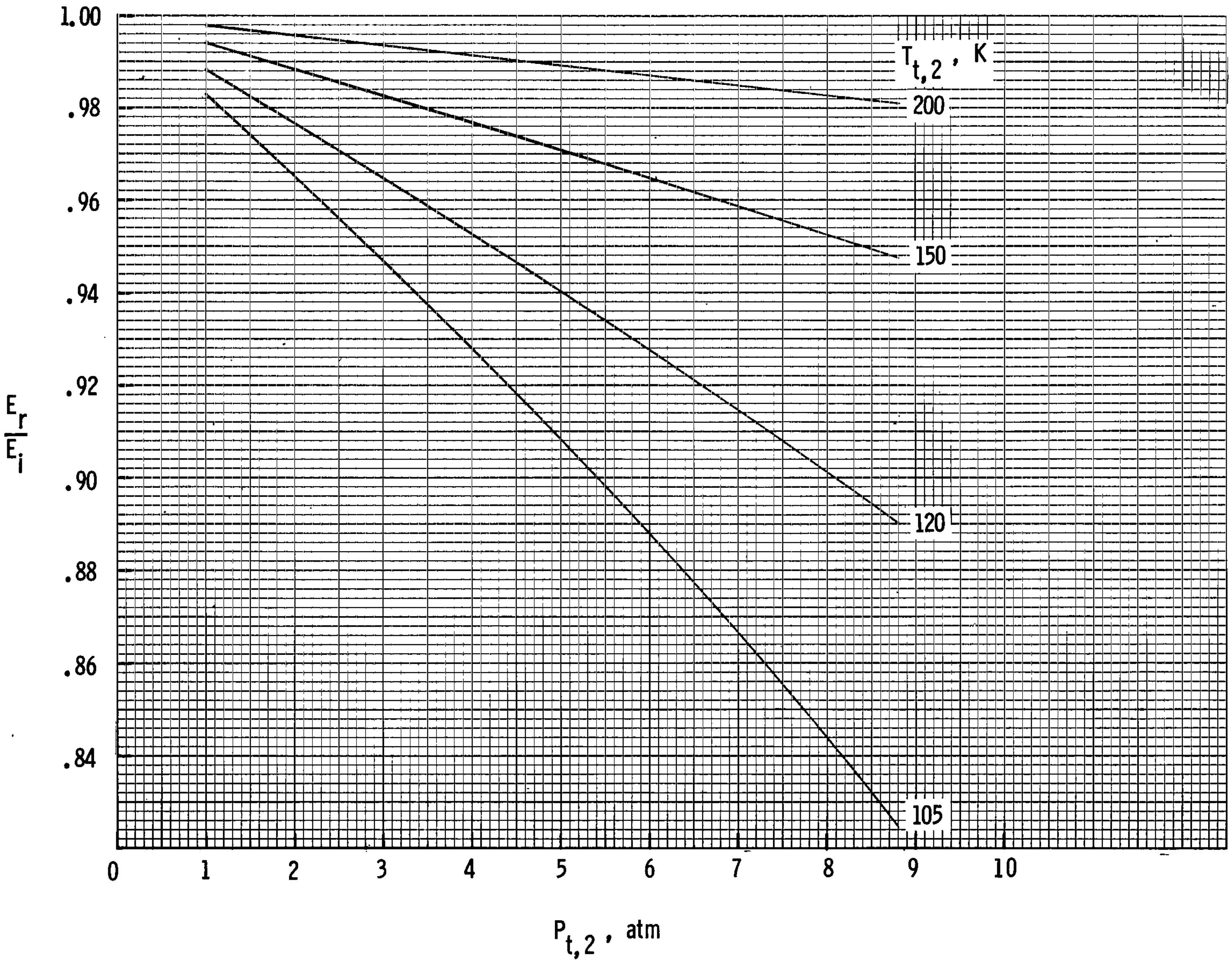
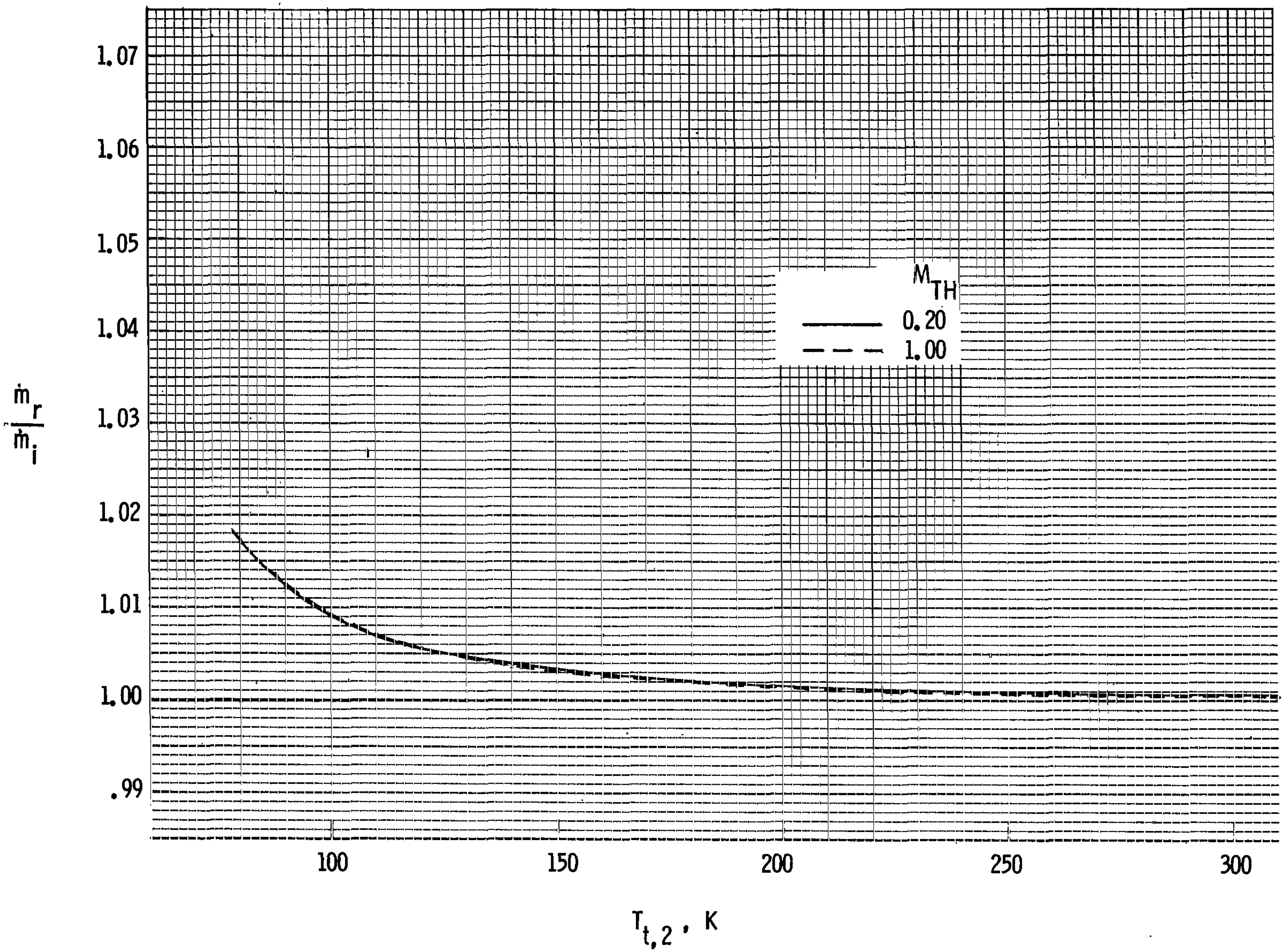
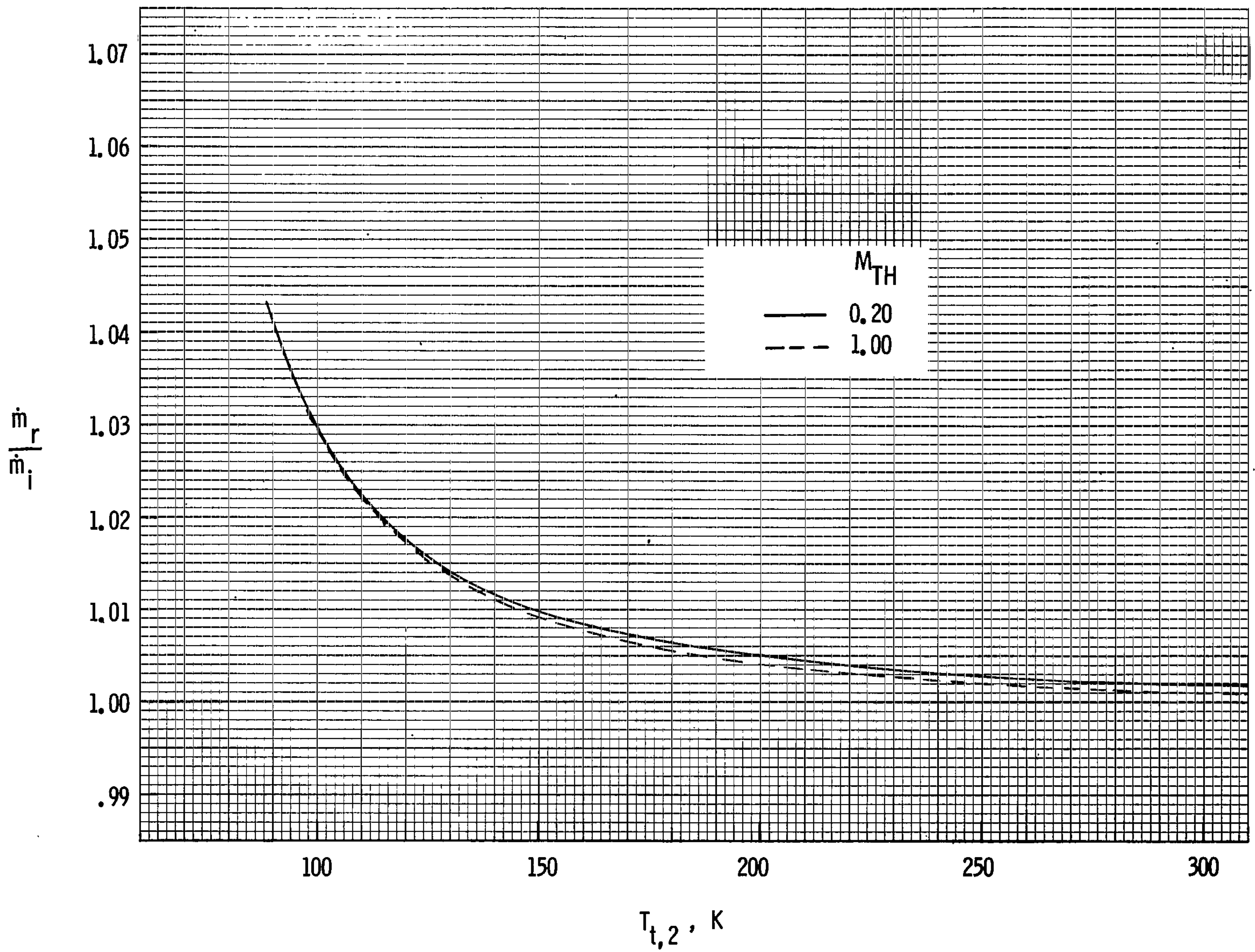


Figure 7.- Variation of isentropic compression energy for nitrogen with stagnation pressure (relative to ideal-gas values). r = 1.025.



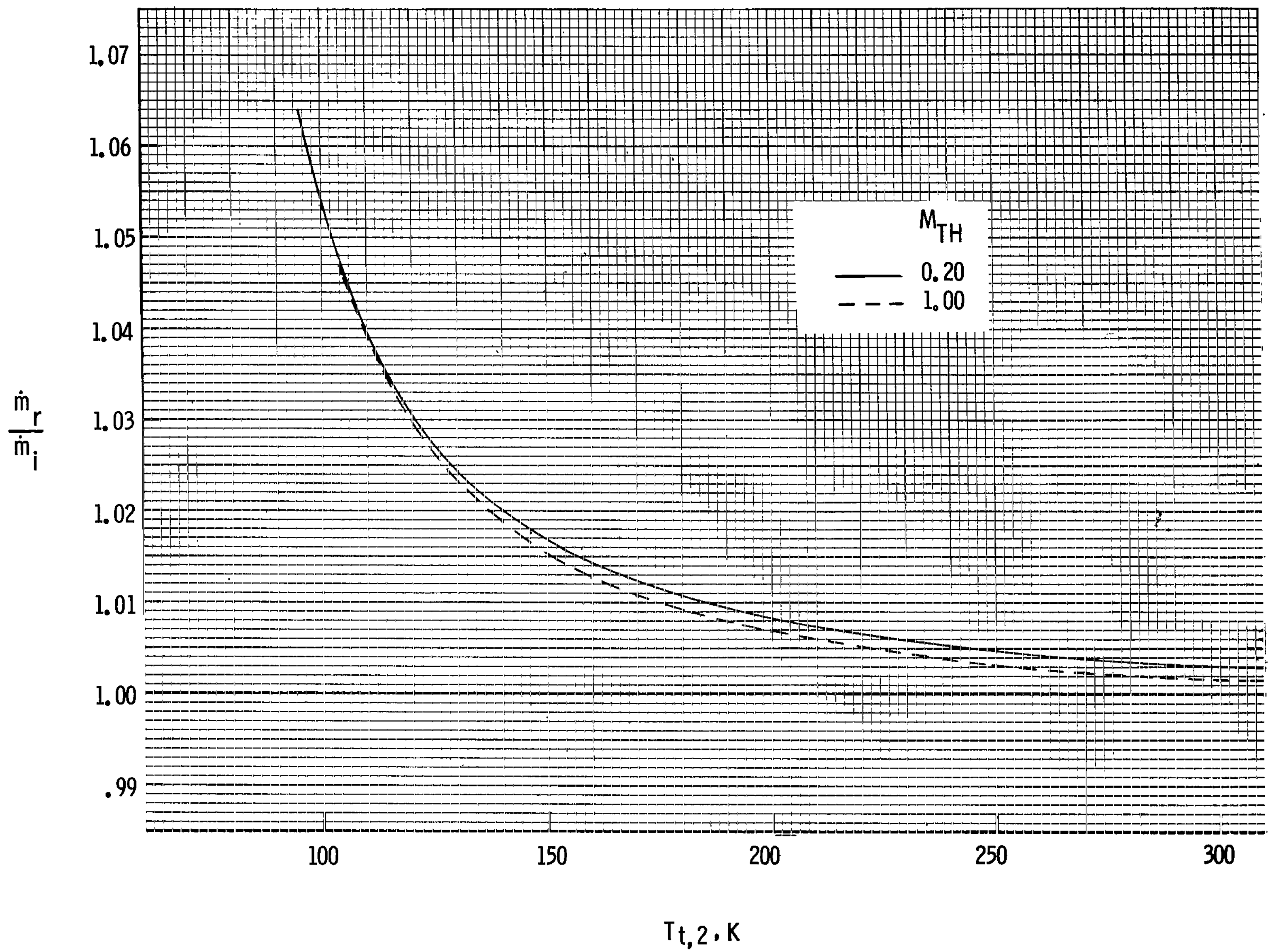
(a) $p_{t,2}$ = 1.0 atm.

Figure 8.- Relative mass-flow rates for various stagnation temperatures and pressures of tunnel throat.



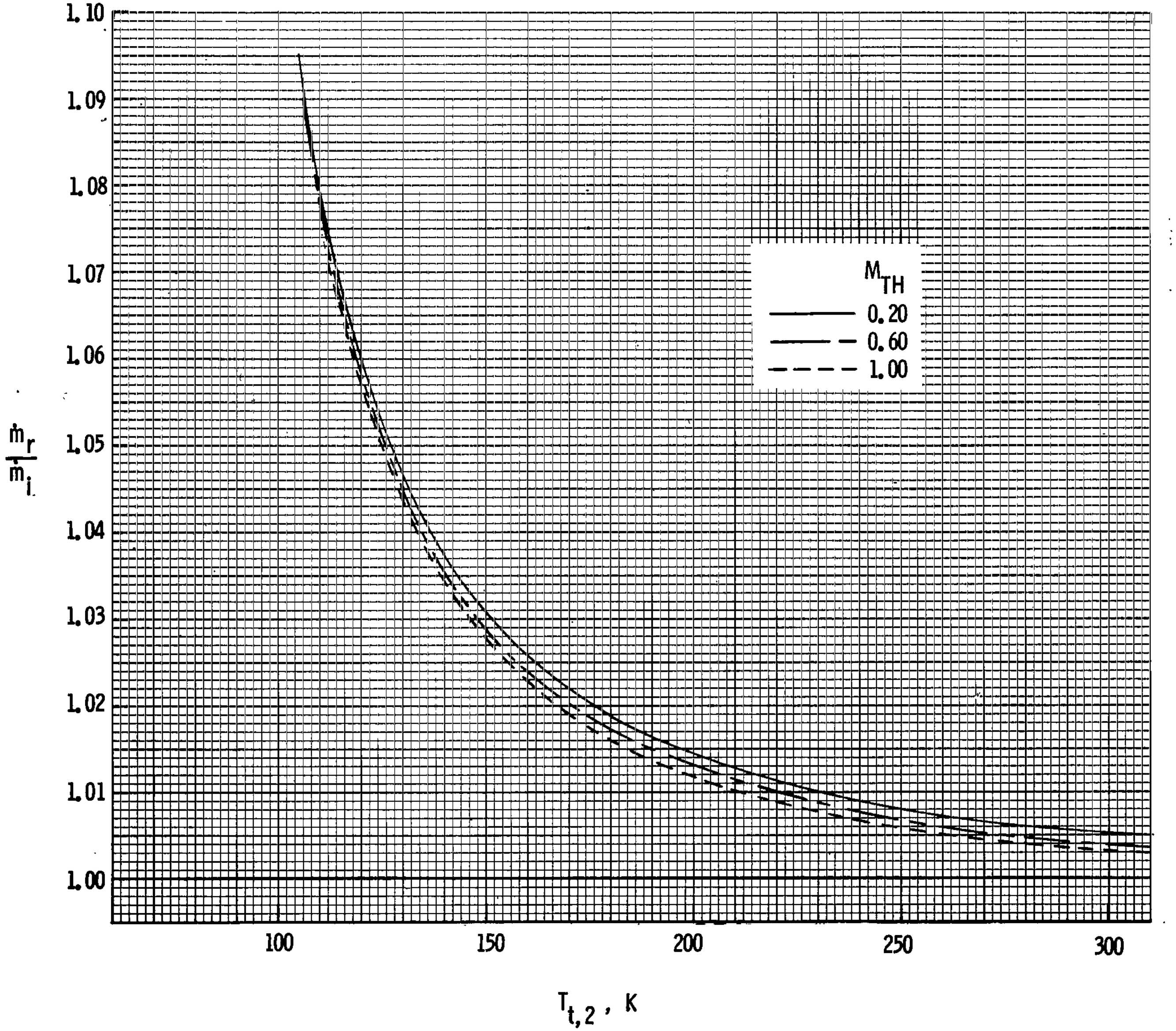
(b) $p_{t,2} = 3.0$ atm.

Figure 8.- Continued.



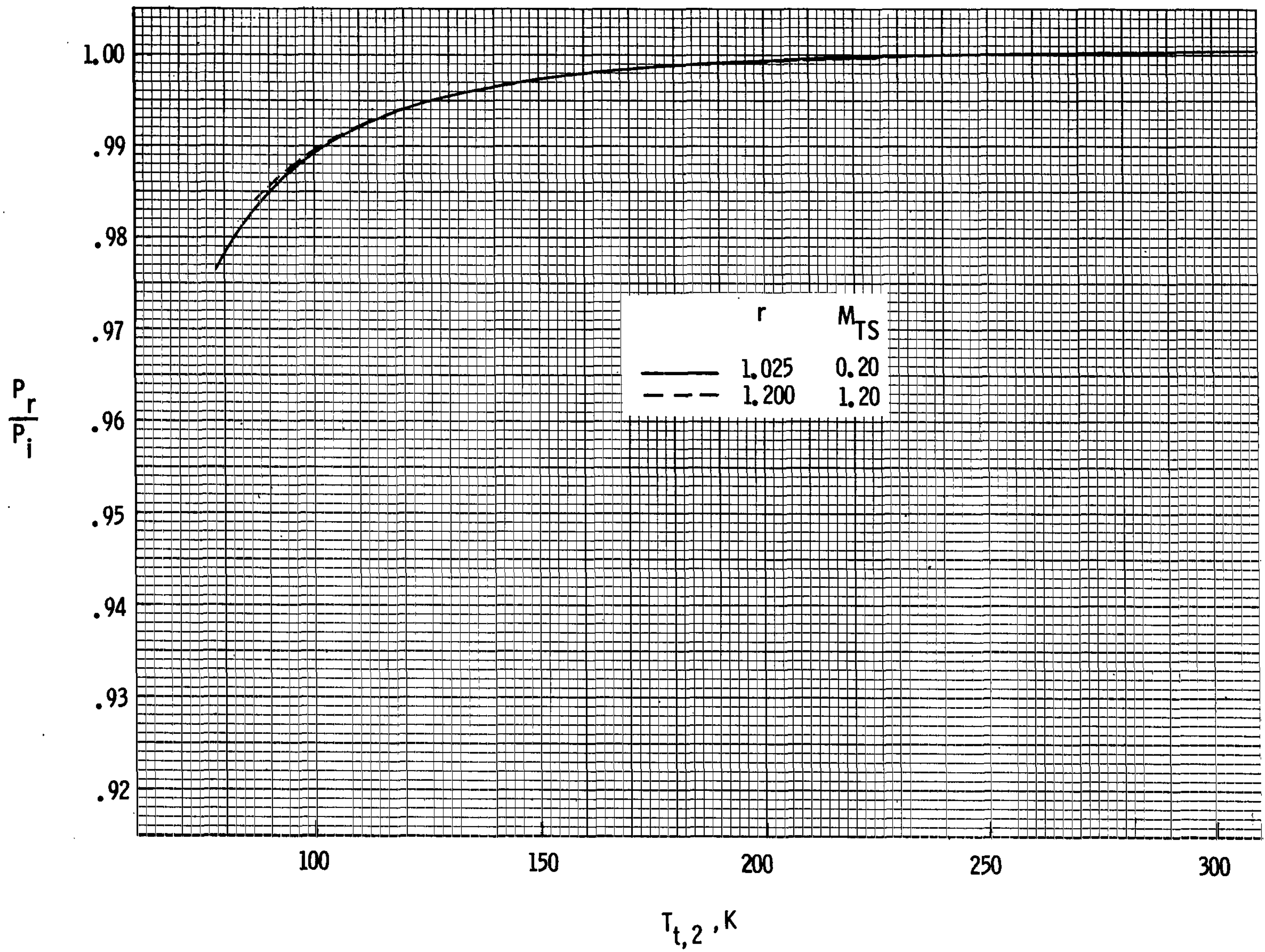
(c) $p_{t,2}$ = 5.0 atm.

Figure 8.- Continued.



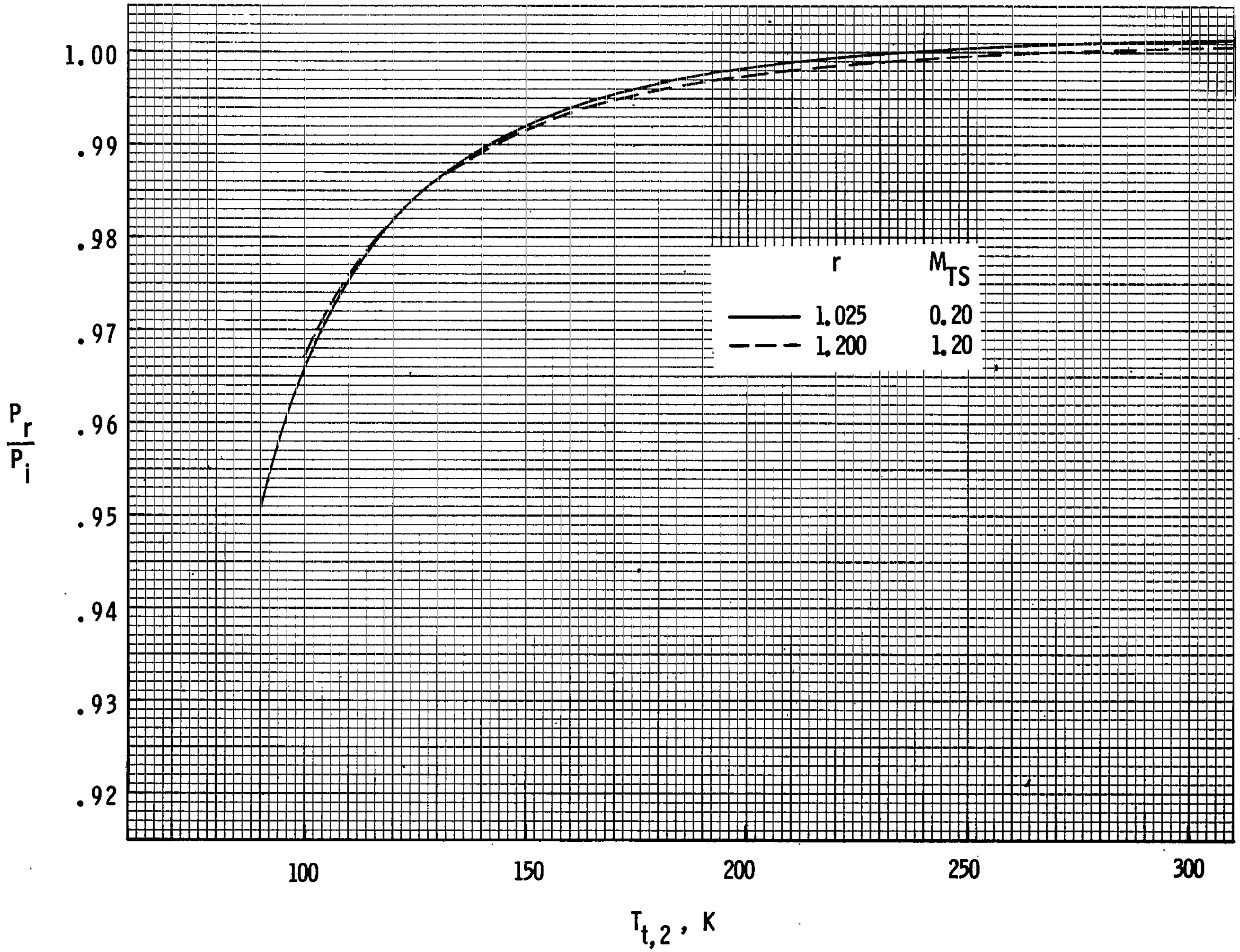
(d) $p_{t,2}$ = 8.8 atm.

Figure 8.- Concluded.



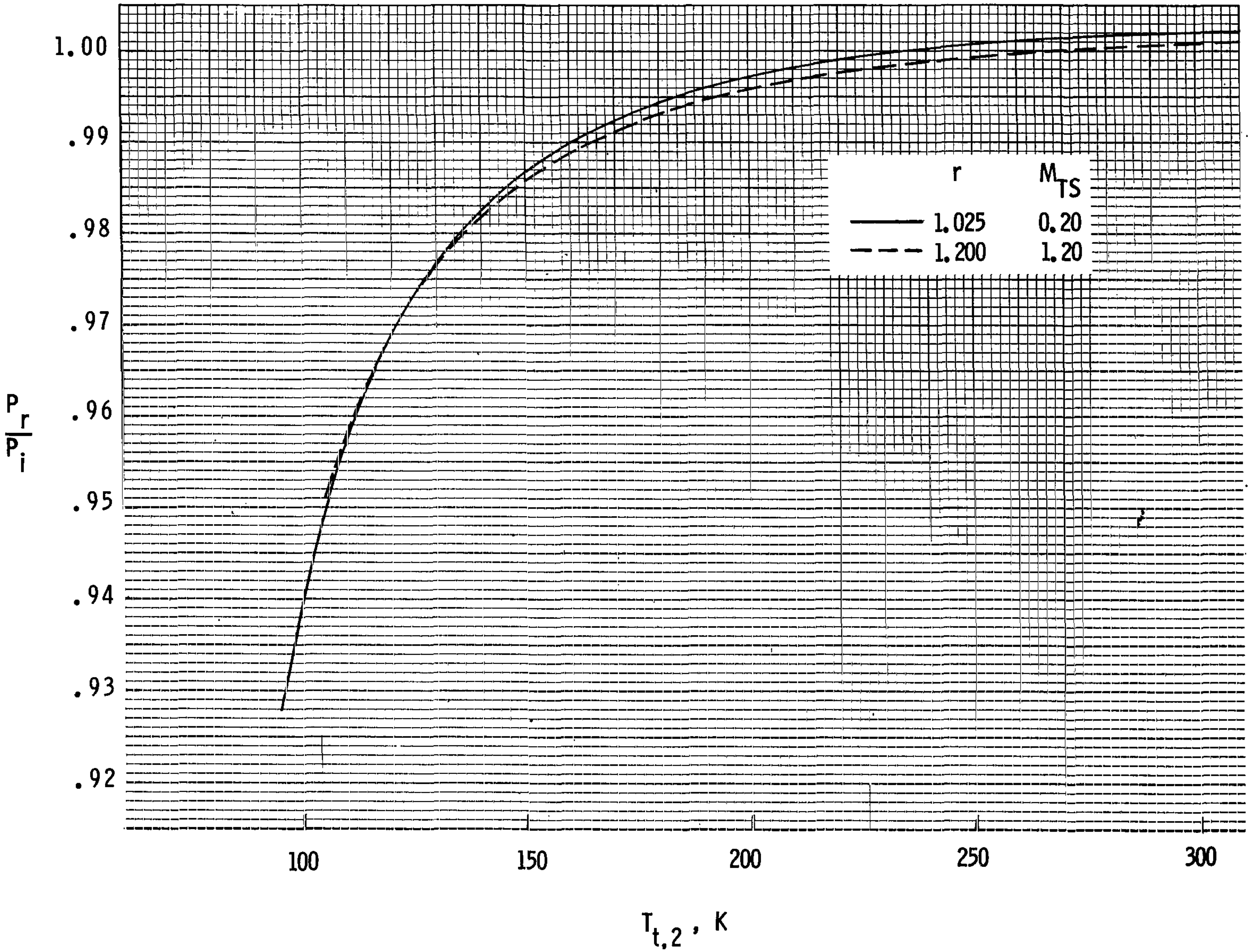
(a) $p_{t,2}$ = 1.0 atm.

Figure 9.- Relative isentropic power values for various stagnation temperatures and pressures.



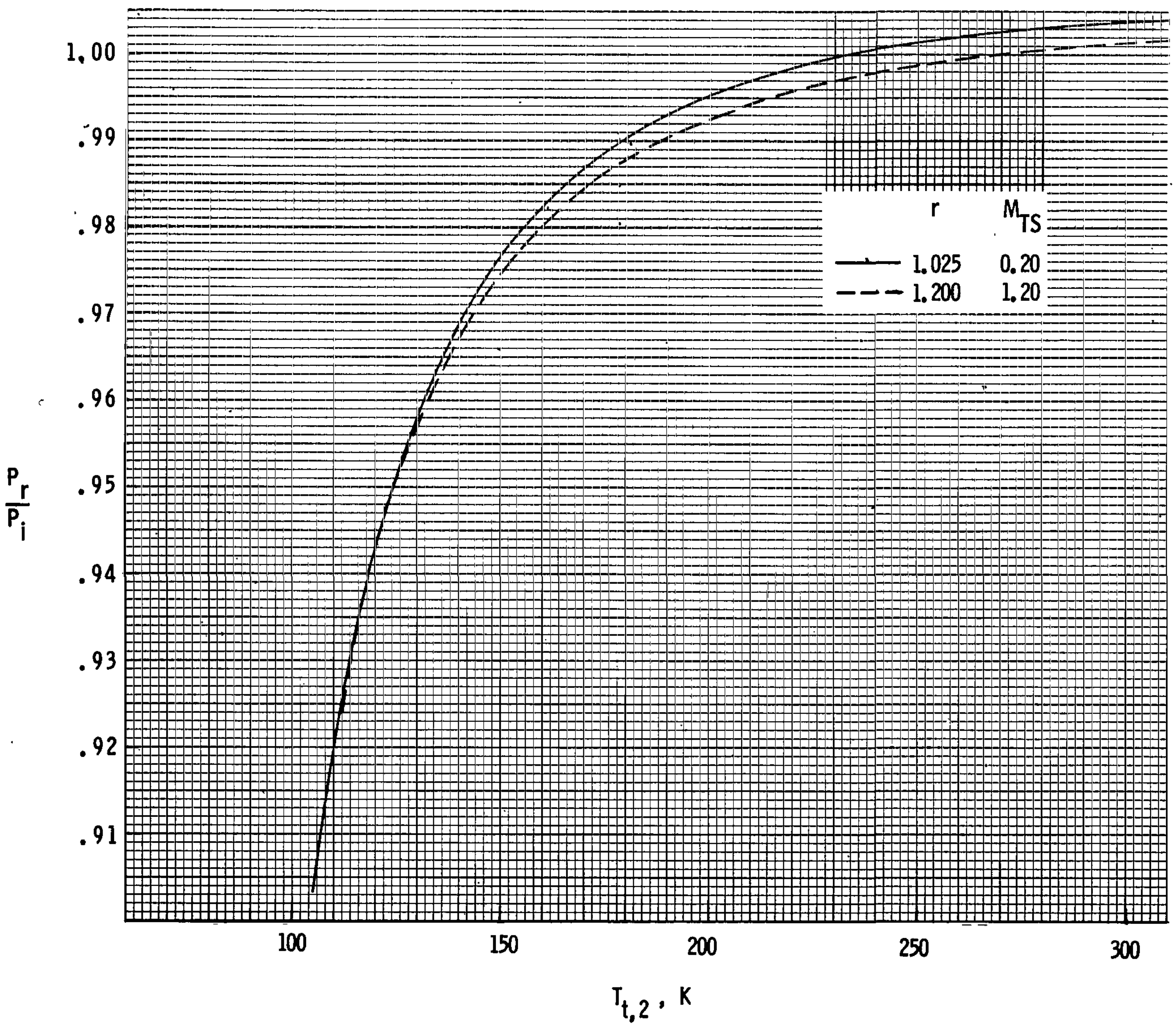
(b) $p_{t,2}$ = 3.0 atm.

Figure 9.- Continued.



(c) $p_{t,2} = 5.0$ atm.

Figure 9.- Continued.



(d) $p_{t,2}$ = 8.8 atm.

Figure 9.- Concluded.

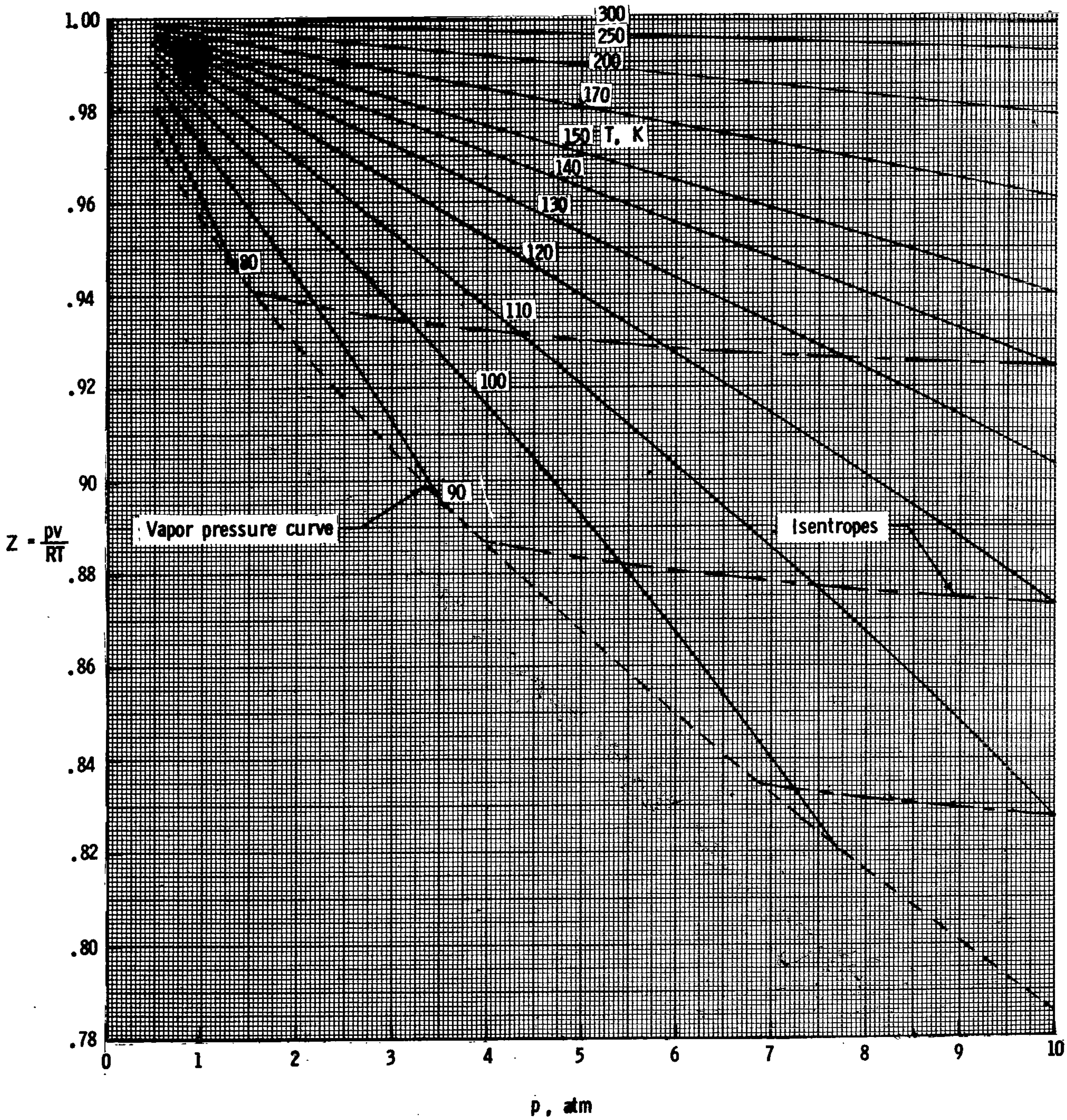


Figure 10.- Compressibility factor for nitrogen (ref. 7).

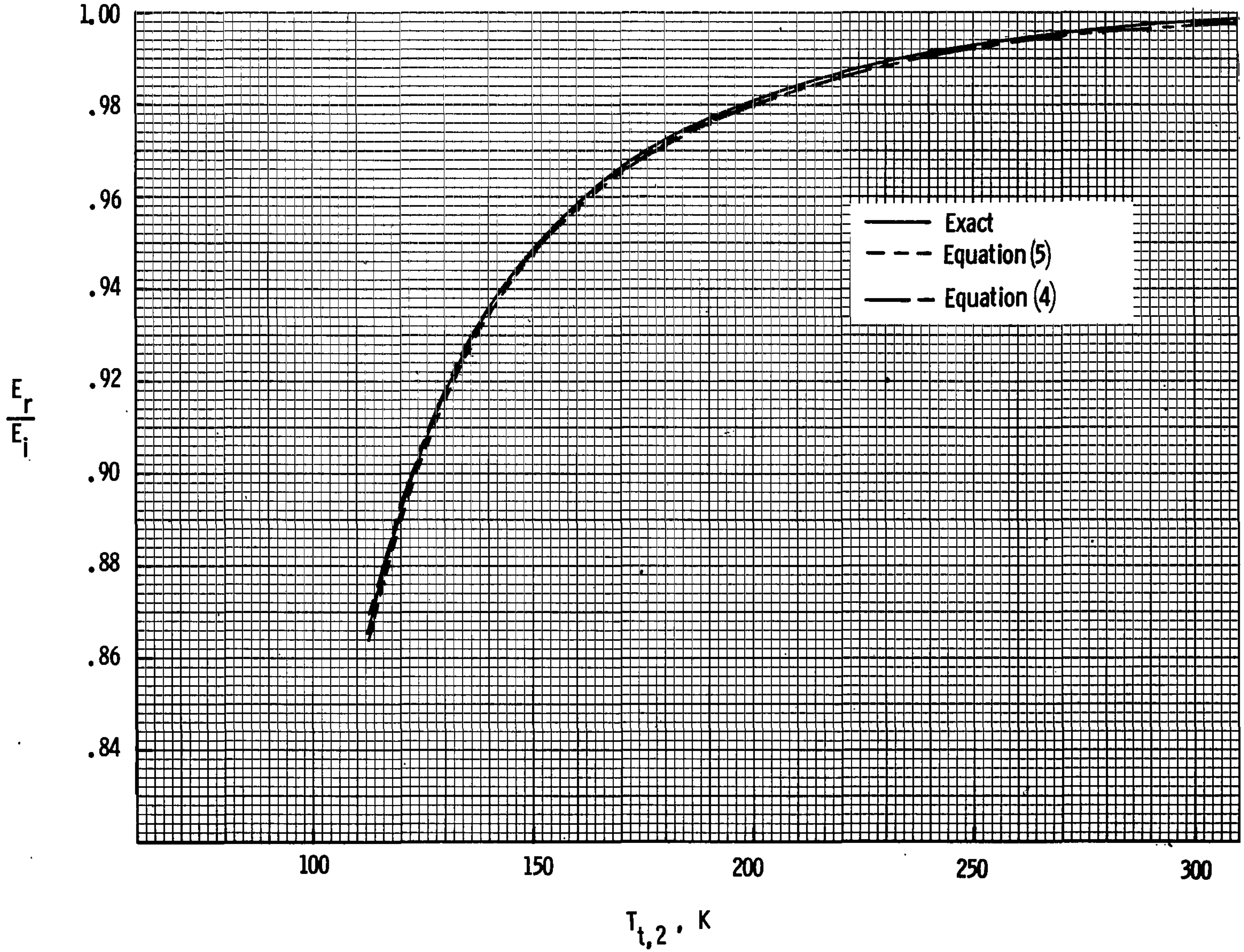


Figure 11.- Estimates of energy for isentropic compressions of nitrogen compared with exact values. $p_{t,2} = 8.8$ atm; $r = 1.20$.

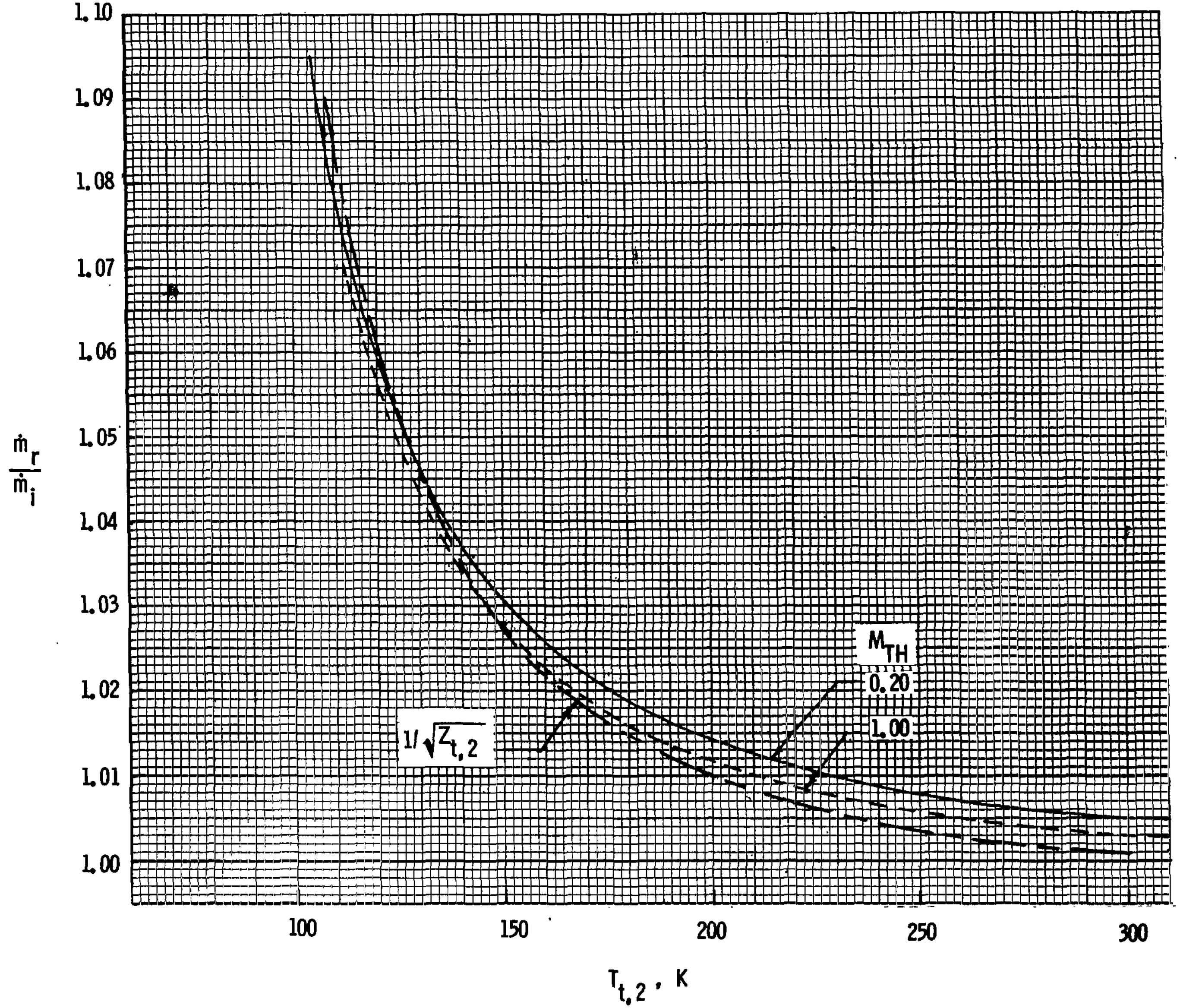


Figure 12.- Approximation for real-gas mass-flow rates of nitrogen (isentropic flow).

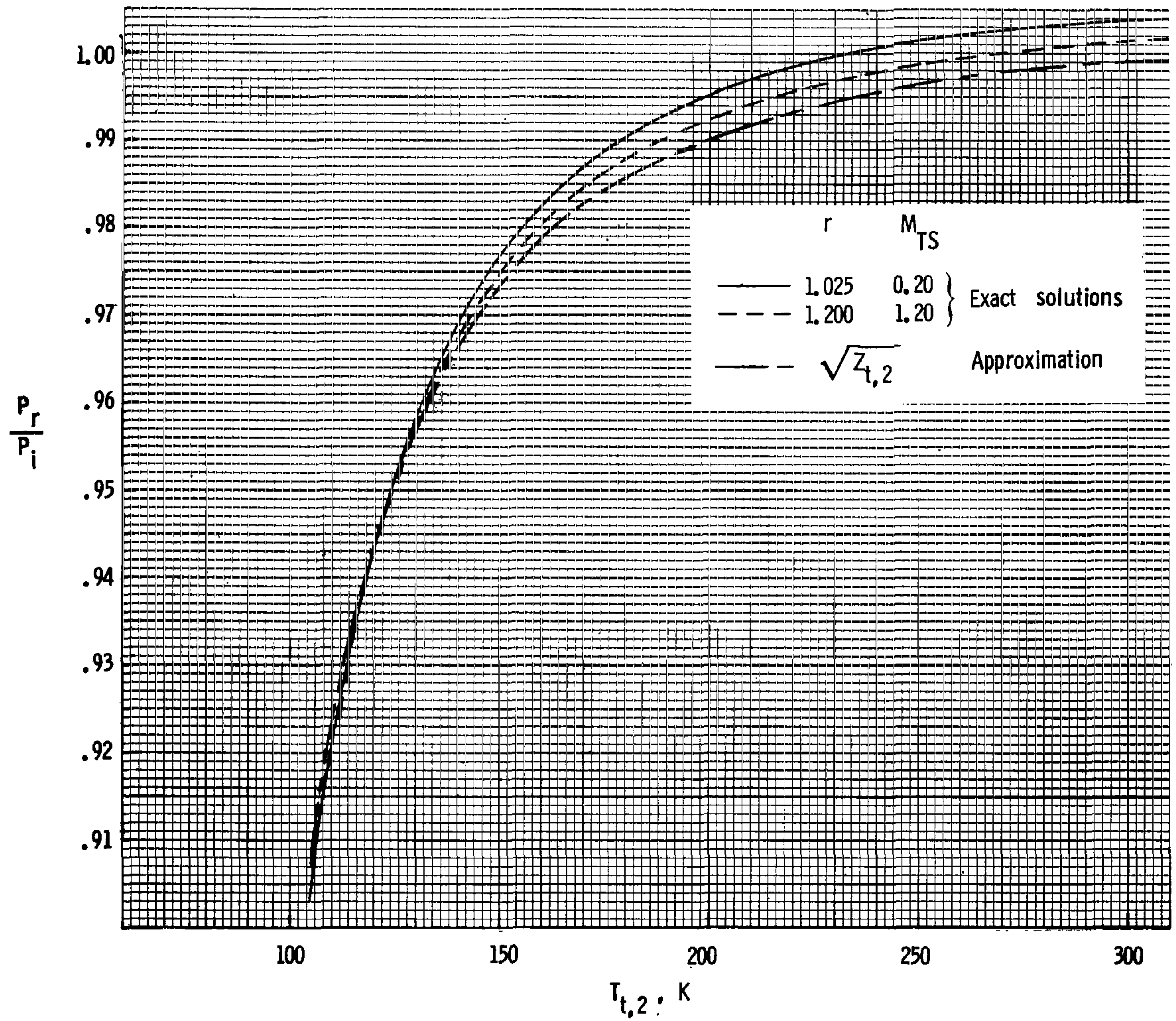


Figure 13.- Approximation for power required for isentropic compressions of nitrogen.

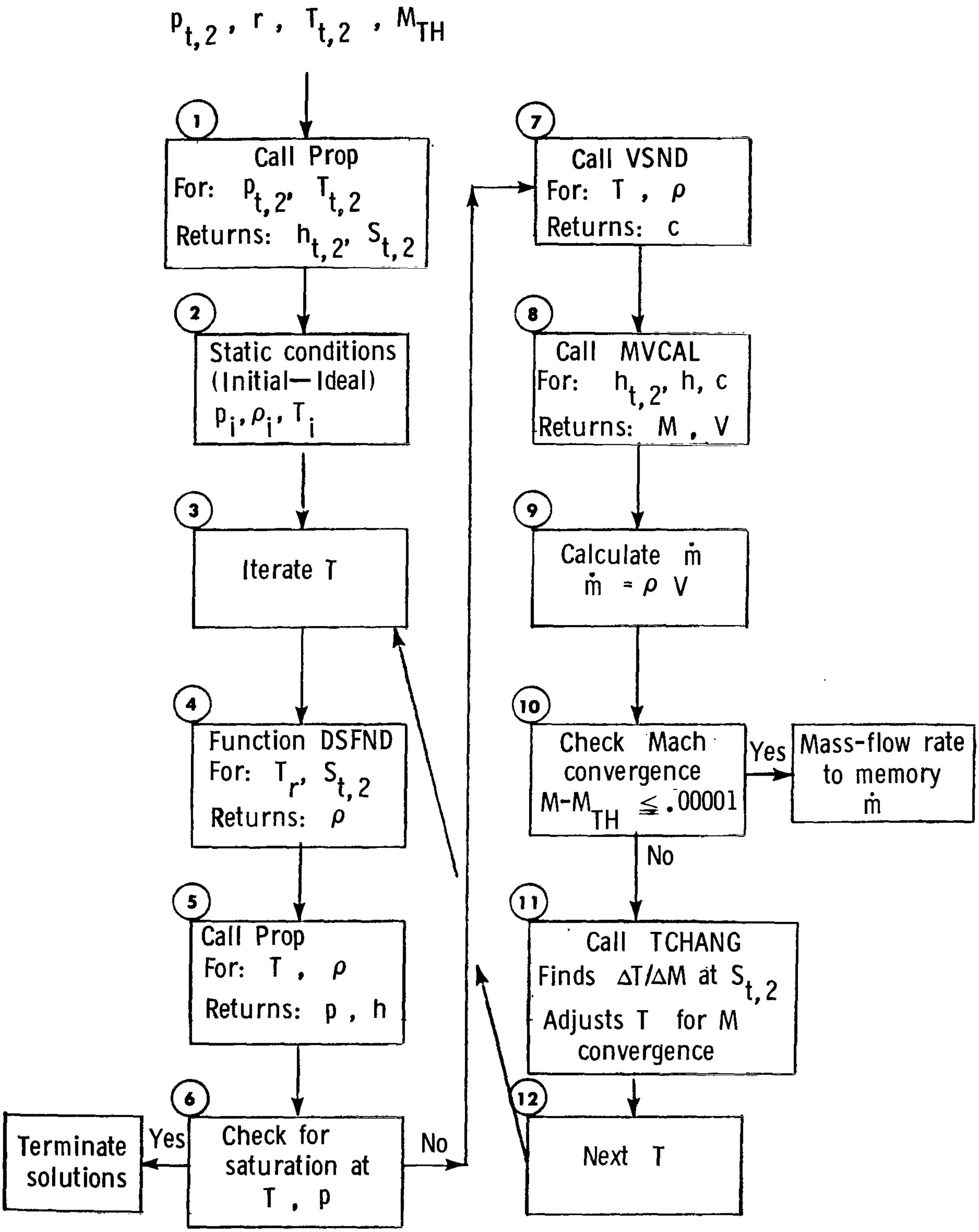


Figure 14.- Flow chart of real-gas calculations of tunnel throat conditions.

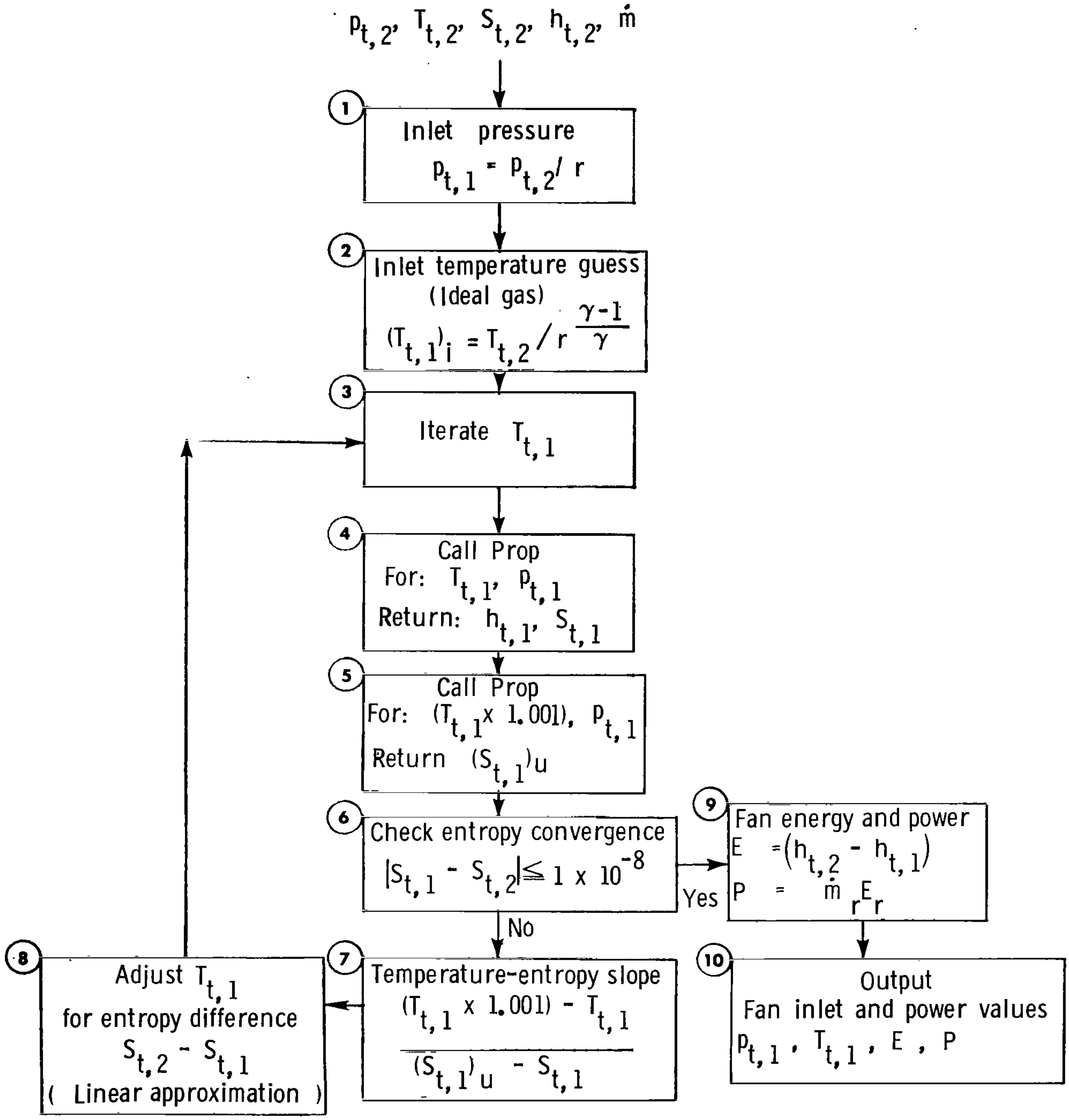


Figure 15.- Flow chart for real-gas calculations of fan parameters.

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